A HEYWOOD PUBLICATION

British Chemical Engineering

THE JOURNAL DEVOTED TO THE TECHNIQUES OF CHEMICAL ENGINEERING APPLIED TO INDUSTRY

MAY 1959
Vol. 4 No. 5

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The cover photograph taken at the Mobiloil Co. refinery at Coryton, Essex, shows the tube bundle of an exchanger removed for cleaning. Crude oil feed is the tube-side fluid and vacuum column bottoms the shell-side fluid.

BRITISH CHEMICAL ENGINEERING is published monthly by HEYWOOD & CO. LTD., Drury House, Russell Street, Drury Lane, London, W.C.2 (Tel.: TEMple 3422), on the 20th of the preceding month. Annual subscription £2 U.K., £2 10s. 0d. sterling overseas for 12 issues post free ($7.50 U.S.A. and Canada) or by standing order through newsagents at 2s. 6d. a copy net. BRANCH OFFICE: Royal Buildings, 2 Mosley Street, Manchester, 2. Tel.: Central 9935 © Heywood & Co Ltd., 1959. Must not be reproduced without written permission.

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Résumés

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ANALYSE THÉORIQUE DE LA CONTAMINATION DES SURFACES THERMIQUES

par D. Q. Kern et R. E. Seaton

Par moyen de la dynamique classique des fluides, l'auteur établie des formules transitoires démontrant théoriquement que les installations industrielles thermiques peuvent être construites de façon qu'il n'est plus nécessaire d'interrompre leur fonctionnement par suite de contamination des surfaces thermiques.

B.C.E., 4, No. 5, 264. U.D.C. No. 66.045.5.

LA RÉSISTANCE DE LA PHASE LIQUIDE PENDANT LE REFROIDISSEMENT PAR L'EAU

par G. Cribb

L'auteur démontre qu'une résistance de la couche liquide à la transmission de chaleur existe dans les refroidisseurs à gaz operant sur le système du contact direct. Il conclue néanmoins que cette résistance peut être négligée en ce qui concerne la construction. Il présente une méthode simplifiée pour la détermination de la relation entre la conductivité de chaleur de la couche liquide et le coefficient de transmission des masses de la couche gazeuse.

B.C.E., 4, No. 5, 267. U.D.C. No. 661.183.1: 541.183.1.

DES SORBENTS SÉLECTIFS NOUVEAUX: LES CRYSTAUX POREUX EN QUALITÉ DE FILTRES MOLÉCULAIRES

par R. M. Barrer

Des excellents sorbents-tamis moléculaires se rencontrent dans le groupe zéolite des minéraux. Quelques zéolites synthétiques sont disponibles sur le marché et beaucoup d'analogues du type naturel ont été synthetisés. L'action de tamis moléculaire peut être complète ou partielle selon les conditions physiques et les dimensions relatives des molécules en cours de séparation. Dans le cas où tous les types peuvent être sorptionnés, des sélectivités très differentes de celles trouvées dans les sorbents classiques sont souvent rencontrées. Ces differences peuvent aussi conduire à des séparations utiles.

B.C.E., 4, No. 5, 280. U.D.C. No. 620.199: 66.012.1.

LES ESSAIS DE CORROSION DANS LES INSTALLATION CHIMIQUES

par R. S. Thornhill

L'auteur donne des indications pratiques sur la découverte et la mesure de la corrosion. Quelques appareils d'épreuve sont aussi proposés pour la mesure des taux de corrosion locale dans les différentes parties de l'installation. Une liste des matériaux de construction possibles est dressée.

B.C.E. 4, No. 5, 286. U.D.C. No. 621.351.

DES TYPES NOUVEAUX D'ÉLÉMENTS GALVANIQUES UTILISANT LES RÉACTIONS DE COMBUSTION

par J. F. Streatman

Une revue est donnée de l'état actuel du développement de l'élément galvanique utilisant les réactions de combustion, aussi que des problèmes empêchant son application, tel que la construction d'électrodes mécaniquement résistants. Un procédé utilisant du combustible solide, de l'oxygène et des éléments galvaniques du type décrit pour la production d'énergie électrique est consideré.

Kurzreferate

B.C.E., 4, No. 5, 258. U.D.C. No. 66.045.1: 620.191.2.

THEORETISCHE ANALYSE DER VERUNREINIGUNG VON THERMALOBERFLÄCHEN

von D. Q. Kern und R. E. Seaton

Mittels der klassischen Strömungslehre werden zeitweilige Gleichungen abgeleitet, die theoretisch nachweisen, dass technische Thermalanlagen derart geplant werden können, dass sie wegen Verunreinigung der Thermaloberflächen niemals stillgelegt zu werden brauchen.

B.C.E., 4, No. 5, 264. U.D.C. No. 66.045.5.

FLÜSSIGKEITSPHASENWIDERSTAND BEI DER WASSERKÜHLUNG

von G. Cribb

Der Autor zeigt, dass ein Widerstand der Flüssigkeitsschicht zur Wärmeübertragung in Gaskühlern des Direktkontaktsystems wohl existiert, gelangt jedoch zu dem Schluss, dass dieser für Planungszwecke nicht berücksichtigt zu werden braucht. Er beschreibt eine abgekürzte Methodik zur Ermittlung des Verhältnisses zwischen der Wärmeleitungsfähigkeit der Flüssigkeitsschicht und der Massenübertragungszahl der Gasschicht.

B.C.E., 4, No. 5, 267. U.D.C. No. 661.183.1: 541.183.1.

NEUARTIGE SELEKTIVSORBENTE: PORÖSE KRYSTALLE ALS MOLEKULARFILTER

von R. M. Barrer

Ausgezeichnete molekulare Siebsorbente werden in der Zeolithgruppe von Mineralien gefunden. Einige synthetische Zeolithe sind auf dem Markt erhältlich und viele Analoge der Naturart sind synthetisch hergestellt worden. Die molekulare Siebwirkung kann je nach den physischen Bedingungen und den Relativabmessungen der zu teilenden Molekülen teilweise oder vollständig erfolgen. Wenn alle Arten erfasst werden, so trifft man oft Selektivitäten, die sich von denen der klassischen Sorbenten weitgehend unterschieden. Diese Unterschiede können wiederum zu brauchbaren Trennungen führen.

B.C.E., 4, No. 5, 280. U.D.C. No. 620.199: 66.012.1.

KORROSIONSPRÜFUNG IN CHEMIKALIENFABRIKEN

von R. S. Thornhill

Der Autor gibt praktische Hinweise fur die Aufdeckung und Messung der Korrosion. Ausserdem werden verschiedene Prüfapparate für die Messung von örtlichen Korrosionsgeschwindigkeiten in einzelnen Teilen der Anlage vorgeschlagen. Eine Liste von möglichen Konstruktionsmaterialen wird angeführt.

B.C.E. 4, No. 5, 286. U.D.C. No. 621.351.

NEUE ARTEN VON GALVANISCHEN ELEMENTEN MIT AUSNUTZUNG VON VERBRENNUNGSREAKTIONEN

von J. F. Streatman

Eine Übersicht des heutigen Standes des galvanischen Elementes mit Ausnutzung von Verbrennungsreaktionen sowie der Probleme, die seine Anwendung verhindern, z.B. der Herstellung von mechanisch widerstandsfähigen Elektroden, wird gegeben. Ein Vorgang wird besprochen nach welchem fester Brennstoff, Sauerstoff und galvanische Elemente der beschriebenen Art für die Herstellung von Elektroenergie verwendet werden.

Резюме

B.C.E., 4, No. 5, 258. U.D.C. No. 66.045.1: 620.191.2.

ТЕОРЕТИЧЕСКИЙ АНАЛИЗ ЗАГРЯЗНЕНИЯ ТЕРМИЧЕСКИХ ПОВЕРХНОСТЕЙ

Д. К. Керн и Р. Э. Ситон

На основе классической теории протекания выводятся непостоянные уравнения указывающие на возможность такой конструкции технологических термических установок, что устраняется необходимость прерывать действие последних в результате загрязнения термических поверхностей.

B.C.E., 4, No. 5, 264. U.D.C. No. 66.045.5.

СОПРОТИВЛЕНИЕ ЖИДКОЙ ФАЗЫ ПРИ ОХЛАЖДЕНИИ ВОДОЙ

Г. Крибб

Автор указывает, что сопротивление жидкой пленки теплопередаче существует в газовых холодильниках системы непосредственного контакта, но приходит к заключению, что для целей конструкции этим фактором можно пренебречь. Описывается упрощенная методика для определения отношения между теплопроводимостью жидкой пленки и коэффициентом массопередачи газовой пленки.

B.C.E., 4, No. 5, 267. U.D.C. No. 661.183.1: 541.183.1.

НОВЫЕ СЕЛЕКТИВНЫЕ СОРБЕНТЫ: ПОРИСТЫЕ КРИСТАЛЛЫ В КАЧЕСТВЕ МОЛЕКУЛЯРНЫХ ФИЛЬТРОВ

Р. М. Баррер

В группе зеолитовых минералов можно найти отличные молекулярные ситовые сорбенты. На рынке существует несколько искуственных зеолитов, а также синтетических аналогов натуральных типов. Молекулярное ситовое действие может быть полным или частичным в зависимости от физических условий и относительных размеров разделяемых молекул. В случаях когда происходит сорбция всех типов, часто встречаются селективности, весьма различные от встречаемых в обычных сорбентах. Эти различия могут также приводить к практически выгодным разделениям.

B.C.E., 4, No. 5, 280. U.D.C. No. 620.199: 66.012.1.

ИСПЫТАНИЯ КОРРОЗИИ В ТЕХНИЧЕСКИХ УСТАНОВКАХ

Р. С. Торнхилл

Статья содержут практические руководства в связи с обнаружением и измерением коррозии. Предлагаются варианты испытательных аппаратов для измерения скоростей местной коррозии в отдельных частях установки. Приводится список соответствующих конструкционных материалов.

B.C.E. 4, No. 5, 286. U.D.C. No. 621.351.

НОВЫЕ ТИПЫ ГАЛЬВАНИЧЕСКИХ ЭЛЕМЕНТОВ, ИСПОЛЬЗУЮЩИХ РЕАКЦИИ СЖИГАНИЯ

Дж. Ф. Страатман

Обсуждается уровень развития гальванических элементов, использующих реакции сжигания, а также проблемы, препятствующие их применению, так напр. создание механически прочных электродов. Рассматривается процесс, употребляющий твердое топливо, кислород и гальванические элементы описанного типа для производства электроэнергии.

DIGEST

OF INDUSTRIAL AND TECHNICAL DEVELOPMENTS

Budget for Expansion

IT was time that our stagnating economy received some stimulus to expansion and industrial leaders in general consider that this has been provided by the recent Budget. DR. HOBLYN, Director of the British Chemical Plant Manufacturers Association, informed us that the Association as such does not express a view on Budgets. Nevertheless, general feeling appeared to be one of pleasure particularly at the proposals on investment allowances intended to encourage replacement and modernisation of plant.

We have previously (Feb., 1959, p.63) referred to the impact on chemical production of the restrictive policies adopted in this country several years ago. The 1959 "Economic Survey" (HMSO 3s.) shows that the eventual effect on U.K. production in the chemical and allied industries was to slow down its advance so that it rose by only 0.1% from 1957 to 1958. Elsewhere in Europe, as we know from other sources, general industrial expansion continued after ours had stopped and the growth of their chemical industries slowed down only moderately. It was certainly time that we resumed our forward march.

Petrochemical Developments

DEVELOPMENTS in the petrochemical industries were recently reviewed by PROF. FRANK MORTON before the Birmingham and Midlands Section of the Royal Institute of Chemistry (*J.R.I.C.* 1959, Vol. 83, p. 145). In the U.S.A. refineries are being designed to maximise high-octane motor-spirit production, pointed out PROF. MORTON. In the United Kingdom, however, the demand for high-octane motor fuels, although itself increased, has not matched the demand for middle distillate and fuel oil, so that the output of the refineries shows an increase in the percentage of fuel oil and middle distillate, and a decreasing percentage of motor spirit. This pattern of demand has affected developments of new processes in the two areas.

In the U.S.A. all available means have been sought to increase the yield of motor fuel and increase its octane rating. Catalytic and thermal reforming have been expanded and catalytic cracking by both fluidised and moving bed types of units has increased. Processes have been introduced to supplement vacuum distillation as a means of preparing charge stocks for catalytic cracking units. Perhaps the most noteworthy of these is the critical use of solvent extraction.

In the U.K. major developments have occurred not in the gasoline range but in the methods of processing the middle distillates. Platforming—passing the straight-run gasoline in the presence of hydrogen over a supported platinum catalyst—followed by a Udex extraction process with diethylene glycol-water mixture, is used mainly for the production of pure aromatics rather than premier fuels. Attention has been concentrated on methods of removing and recovering sulphur from the various streams, since the Kuwait crude oil so largely used in the U.K. has about 3% of sulphur. Perhaps the most significant development is the process for desulphurising middle distillates (diesel fuels), although it can be used for products in almost any boiling range.

Soviet plans in this field form the subject of an authoritative article in *Khimicheskaya Nauka i Promyshlennost*, 1959, Vol. 4, No. 1, by V. S. FEDOROV, Chairman of the State Committee for Chemistry. The general target of a threefold increase in volume of chemical products over the seven year period 1959-1965 is discussed in terms of individual groups of products. All this will provide useful background for those who will be at least looking through the papers to be presented at the Fifth World Petroleum Congress which opens in New York on May 31.

Pressure Loss in Fittings

AT the Engineering and Marine Exhibition, the Mechanical Engineering Research Laboratory are demonstrating designs of fluid power circuits including one bad example. Their main object however is to emphasise that circuit designers cannot do much without knowing the flow characteristics of the fittings. It is hoped that the exhibit will draw attention to the oil fittings rig which is available at M.E.R.L. for use by manufacturers of valves and other oil hydraulic fittings, to supply information on the head loss characteristics of these fittings. The figures thus derived are evidently of great direct value in oil hydraulic circuits, for the rig can provide hydraulic oil at two viscosities and flow rates up to 250 gal/min under pressures up to 800 lb/sq. in. Temperature of the oil can be held constant to close limits for power inputs up to 150 h.p. Flow controllers and pressure-measuring devices are included to give accuracy to the various measured quantities. But, in addition, results are plotted in such a way as to give maximum application. For instance, if a head loss coefficient is plotted against Reynolds number, it should be possible to show the performance of the fitting for any fluid over the same range of Reynolds number. This means that, although the results have been obtained with oil as the fluid, the same information could be used to predict the head loss characteristics if water were used. If cavitation takes place, this correlation may no longer hold, but for most applications when cavitation is absent, the correlation is considered to be sufficiently good for practical application.

Further valuable information can be obtained by plotting the head loss coefficient against valve opening. The resulting curves show quite plainly the flow regulating characteristic of the valve over its operating range of opening.

Using Statistical Design

THE case for statistically designed experiments becomes much more convincing when it is demonstrated with an example. And although FRED. C. LEONE (of the Ohio Case Institute of Technology) opened his paper* with a general discussion of anonymous Factors A, B, C and D

he went to a specific illustration. Consider the examination of four factors in a process, such as agitation speed at 200 rpm and 400 rpm, concentration at 2% and 4%, temperature at 30°C and 50°C, and blade type at type 1 and type 2. MR. LEONE illustrated how it is possible to examine the percentage yield of a reaction as a function of these variables by designing and analysing a fractional factorial experiment.

A factorial design of an experiment is one in which each of the levels of each factor is represented in the experiment. It gives a picture of the complete field of investigation rather than a detailed examination of just a few selected paths. It is, in general, more efficient and more economical than the classical type of experiment. It not only gives information about the main effects, but also about the higher order combinations (or interactions) of these effects. However it is possible by statistical juggling to take half the full factorial by first deciding on an effect one is willing to lose initially. This is called the defining contrast. After settling this, the analyst splits all of the treatments into two sets, or blocks, and chooses one of the two.

Of course there is more to any statistical analysis than just stating whether a factor is significant or not. There are further inferences, comparisons, confidence statements, and finally, a discussion of the physical conclusions of the experiment. All this is clearly pointed out by MR. LEONE who concludes, for the sceptics, with a statement of faith: "these techniques will not make a bad experiment good. But they will allow you to obtain better results, more meaningful results, out of a good experiment."

* Presented to the A.I.Ch.E. Spring Meeting.

Cracking Methane in an A.C. Arc

INCONCLUSIVE results were reported by ING. M. HANGANUT and ING. A. ROSENBERG* after a pilot-scale investigation of methane cracking in an a.c. arc and comparison of performance with that in a d.c. arc. Assuming complete conversion of the methane into acetylene the maximum theoretical yield would be 25% by volume of the products. The actual yield in a d.c. arc is 14% acetylene, being a compromise between the steep increase in consumption of energy associated with higher concentrations of acetylene and the difficulties and increased cost of concentrating lower yields of acetylene.

Carrying out the process in an a.c. arc has certain technical and economical advantages but also presents some new problems. One of these is the difficulty of maintaining a continuous electric arc. This may be solved by incorporating a choke in the circuit, the effect of which is to cause a phase shift between current and voltage and to produce a high-voltage discharge just as the arc is about to extinguish itself. The second problem is associated with the fact that re-ignition of the arc requires a voltage two-to-three times that which is effective in maintaining the arc. This means that more power must be supplied than is necessary and results in a poor power factor. In the opinion of the authors this is the most important difficulty hindering the successful development of this process.

Experiments designed to test the effect of decreasing the distance between the electrodes showed that a maximum power factor is obtained for a distance of 4-5 mm as compared with 4 mm for d.c. arc; reducing the distance decreases the re-ignition voltage, while increasing it leads to a large delay in the striking of the arc as a result of an increase in the re-ignition voltage. Several other variables were also examined.

The effects of preheating the gases are very complicated and the authors were not able to analyse these satisfactorily. Flow of gases through one of the electrodes only instead of both, affects the passage of current through the reactor and may under certain conditions completely suppress one of the half-waves. Evacuating the gases through both electrodes restores original conditions. Increasing the speed of rotation of the gases increases the effective voltage across the arc while at the same time leaving the re-ignition voltage unaffected. In this way a power factor of 0.4 was achieved as compared with 0.75 for the d.c. experiments.

* *Revista de Chimie*, Jan. 1959, p.23.

Corrosion and Passivity

ANYONE concerned with corrosion is also necessarily interested in passivity. Since both phenomena are essentially electrochemical, interpretation of voltage-current curves obtained by potentiometric methods has helped investigators to discern the characteristics of passivity. In a recent paper in *Corrosion et Anti-Corrosion* (vol. 7, No. 3, 1959, p.83) U. F. FRANCK summarises the evidence showing that the passive state is due to very fine continuous films formed on the surface of the metal presenting particular properties of electrical conductivity. It follows that the behaviour of passivated metals is determined in the first place by the chemical and electrical properties of the covering film and not by those of the metal itself. The films are extraordinarily thin—of the order of 10 to 100 Angstrom units—and well below the limit of visibility.

PROF. FRANCK points out that the explanation and delimitation of passivity are personal matters and not a definable principle. His paper therefore is presented almost as a personal *credo* but well-backed by material on conditions of formation and destruction of passivated films and of their main properties. This includes curves and data on their conductivity, kinetic reaction instability, and sensitivity to halogen ions on which the passivity depends.

Canadian Chemical Engineering Research

IN the latest review of the National Research Council of Canada (1958) there is a useful account of the work in progress in their chemical engineering section. It may be recalled that in 1952, the Division of Chemistry was divided into separate divisions for pure and for applied chemistry. Chemical engineering forms a part of the latter and the pattern of the programme indicates this emphasis. For example fundamental studies in a number of projects, as well as their engineering and development aspects, have been undertaken during the year. Typical of these has been the work related to the oxidation of olefins to useful chemical intermediates. Arising from the main problem of improving the performance of the catalyst, associated studies on sintering of the metal, changes of surface area of the catalyst with reaction time, and development of special analytical procedures have been undertaken. In the inorganic group, studies on the crystal structure of arsenides of iron, cobalt and nickel have been extended to include all of the compounds formed in these systems. Magnetic susceptibilities of these metal-metalloid compounds are being determined over an appreciable temperature range. Crystallographic investigation of the complex oxides formed by NiO and As_2O_5 and by CoO and As_2O_5 have been completed.

At the same time there has been work on reactors for olefin oxidation and studies to assess the feasibility of using

the fluidised bed procedure on a number of chemical reactions of interest to industry. Among these were the halogenation of boron compounds, roasting of speiss to remove arsenic, and pryolysis of wood waste to produce liquid products.

Using slurries of calcium carbonate as model suspensions, data were obtained with various feeding arrangements in a large single leaf inclined settler. These data are useful in the development of scaled-up models. The design of a multi-compartment unit consisting of 20 cells, which was subsequently built and operated on an experimental basis, was suggested to an interested company.

Compressors for Light Hydrocarbon Gases

CHOICE of a compressor for light hydrocarbons depends on the quantity handled and on their physical and chemical properties. For large quantities turbo-compressors are most suitable, except for methane. Hydrocarbons have low adiabatic exponents which vary with temperature. Thus relatively high compression ratios (4-6) can be used and a low number of stages. Corrosion troubles are due to sulphur compound impurities and the diluent action of hydrocarbons on the lubricating oils. Hence special greases are often necessary.

Centrifugal compressors are also a convenient choice for large throughputs but occasionally there is trouble due to deposits affecting the rotor stability. Turbo-compressors are used up to 35 atm. For amounts up to 20,000 Nm^3/h and pressures to 12 atm Lysholm screw compressors are used: no lubrication is necessary. However reciprocating piston compressors are also widely used for these duties. The latter are also applied for raw hydrocarbons which require 30-50 atm with compression ratios of 4-5 and 2-3 stages. These compressors carry 10-15% dead space which lowers efficiency at high compression ratios and high compression and expansion polytropic exponents (1-1.2) so that careful choice is necessary between the number of stages and the compression ratio. With these, the greatest problem is wear due to water and the hydrocarbons diluting the lubricants. Wear can be reduced by hard surface pistons, heating of cylinders, special rings and greases.

A review of this field has been given in a recent issue of *Strojirentsvi* (Vol. 8, No. 12, p. 898) by ENG. V. VEK who concludes by referring to safety aspects. Relatively high concentrations are necessary for hydrocarbon-oxygen mixtures to explode, but there are health hazards. Attention must be paid to the risk of skin disease, narcotic effects and poison gases such as H_2S occluded in the liquid hydrocarbons.

Has the Oblong Ejector any Advantage for Stationary Plant?

TO meet the specific problems of locomotive draughting —15 tons of steam per hour ejecting 30 tons of gas against a pressure differential of perhaps 10 in. of water in a unit of 5 ft. long—DR. A. GIESL-GIESLINGEN of Vienna produced an oblong multi-jet ejector. This has been tested on locomotives in several countries and confirmed to give greatly increased capacity. Present patent protection (B.P. 683,234) is limited to this use.

One basic factor which contributes to the improved performance is the reduction of the shock loss incurred during the mixing of gas and steam down to a small fraction of the loss in present designs. When we asked DR. GIESL-GIESLINGEN if his ejector was likely to have wider pumping applications he stated that the advance is far less pronounced in stationary units where enough space is available to develop an ejector of proper size for any given job. It is nevertheless remarkable that the oblong cross-section of mixing chamber and diffuser does considerably reduce wall friction compared with the otherwise equivalent ejector of circular cross-section. This fact, and the short length required for high-capacity ejectors of this kind would seem to justify some interest by chemical engineers in applying this principle.

A typical Giesl ejector (built for freight locomotive Class 81, Belgian National Railways, equipped in December, 1958). Chimney pressed and welded, nozzle of cast iron.

Minimising Human Error

FEW machines or equipments or systems built today make use of existing knowledge about human behaviour; few could not be improved so that more people could learn to use them more quickly and more reliably. This was the kernel of the case by R. CONRAD in a recent paper on engineering psychology.* From CRAIK, a pioneer in this field, DR. CONRAD quoted the first systematic formulation of the concept of a man-machine system: "As an element in a control system a man may be regarded as a chain consisting of . . . sensory devices, a computing system, an amplifying system, and mechanical linkages. . . . The problem is to discover in detail the characteristics of this human chain, such as its sensory resolving power, its maximum power output and optimum loads, its frequency characteristics and time-lags. . . ."

Machines may make men commit errors in a number of ways. For instance, the brightness ratio between a light signal and the ambient illumination might be too low. Or as commonly happens, verbal information, such as numbers, may be passed through a communication channel which distorts speech sounds. A further class of breakdown of special interest is called—in this specialist terminology—"failure of the computer link." Several instrument dials may be providing equally important information and the operator's attention must be switched from one to the other and remembered during the intervals. It is quite easy to demonstrate in the laboratory how—with too long an interval—operators can forget the information from an instrument; in a developing process this can lead to error.

This paper is one of the clearest expositions of this

subject which we have seen and we must commend an analysis which points out that the human operator has often been a target for accusations of carelessness, when all that could be said with absolute certainty was that a system had gone wrong.

* To be published in *Trans. Soc. Instr. Tech.*

Separating Fluids from Fibrous Pulps

"ON a small scale the simplest way to separate fluid from a fibrous pulp is to pick up a handful and squeeze it." After this characteristically laconic opening, MR. N. W. PIRIE, F.R.S., of the Rothamsted Experimental Station has recently gone on to survey* current types of press and describe one developed at the Station. Most of the free fluid can generally be expressed from fibrous pulps in a few seconds at 50 lb/in.^{2} if the layer of pulp is kept thinner than 1 in. after it has been pressed, and if the fluid is allowed to run away freely. The need for this time and the frictional properties of many pulps are serious obstacles to design of any strictly continuous press. Roller presses do not allow enough time, screw expellers create too much friction, continuous centrifuges and some other arrangements are intricate and vulnerable. The new machine is an intermittent but automatic press which is thought to avoid these defects. In this the material on a perforated conveyor is pressed by a ram and then moved forward as the ram lifts. One such machine has already been made. Since every problem of juice expression is in some respects a special problem MR. PIRIE points out that one machine is not likely to suit all materials. The conveyor and ram principle is not therefore put forward as a general solution to the problem of getting fluids from fibrous pulps, but it has the merit that there is no relative motion between the press surfaces and the material being pressed while pressure is applied. There are many applications where this feature would be valuable.

* *J. Biochem. & Microbiol. Tech. & Eng.* 1959, Vol. 1, No. 1, p. 13.

Standard Conversion Factors

THOUGH the quainter units may be the first to catch the eye, it is the authoritative statement of metric-British equivalents which gives great value to the new British Standard on conversion factors.* We agree with the B.S.I. view that there is an increasing need to provide the metric equivalents of British units in British Standards generally, for the information of those who use these standards in other countries and who are not familiar with the values of British units. For this and many other purposes the revised standard provides the means of obtaining equivalent values.

This is a second revision of a document first issued in 1930. It deals comprehensively with the conversion of quantities which are in general use in engineering, industry and commerce, and includes the units most frequently used in these fields. The subjects covered are, broadly, metrology, mechanics and heat; the standard does not deal with purely electrical units. Part I is divided into two sections. In Section One, the units used in about fifty different subjects of measurement are given in the order of their subjects, together with some definitions and key conversion factors. From these units the conversion factors given in Section Two are developed. Later it is intended to publish detailed conversion tables for the more frequently used conversions to which reference is continually made in design and inspection, and also in home and overseas trade.

* Conversion Factors and Tables. Part 1. Basis of Tables. Conversion Factors. B.S. 350: Part 1: 1959. 15s.

Heat Penetration in Pressing Plywood

FOREST Products Research Laboratory have reported that the theory of heat conduction in slabs of an ideal material can be used to calculate the heating time of plywood pressed between hot platens whose temperature does not exceed 100°C (212°F). The equation examined was that of CARSLAW and JAEGER* for these conditions in an ideal material. Observed heating times were compared with those obtained by inserting values of board thickness and diffusivity in this equation. It was found† that there may be considerable variation in the results and the calculated times should be increased by about 10% to allow for variation in the thermal properties of the wood and for some heat loss from the edges in the form of water vapour. If the veneers before pressing are over 10% moisture content then the calculated times should be increased by a further amount, which can be, in certain circumstances, as much as 30%.

In addition the "Square Law of Times" was examined. This states that when the surfaces of a slab of material, initially at a uniform temperature, are placed between hot platens maintained at another steady temperature, the time at which any given point in the slab reaches a specified temperature will vary as the square of the thickness of the slab. This applies only to boards which differ in thickness, but not in their constituent materials or in their pressing conditions. Tested with mahogany boards of various thicknesses pressed at 115°C, it was found to give good results in the centres and even, with greater variation, at the edge despite the considerable loss of moisture and heat from the latter position.

* "The Conduction of Heat in Solids." Oxford, Clarendon Press, 1947.
† "Heat Penetration in the Pressing of Plywood." J. F. S. Carruthers. HMSO 1959, 1s. 9d.

The Peaceful Atom

MANY months after the event we are still with difficulty digesting the lessons of the second U.N. Conference on Peaceful Uses of Atomic Energy. The British Nuclear Energy Conference has made its own contribution to this enormous assimilation problem—over 2000 papers were presented—by organising a symposium entitled simply "Geneva 1958." Work on chemical processes was summarised by PROFESSOR J. M. KAY with collaborators and the resulting paper was read by C. J. TURNER, Deputy Director of Chemical Plants at Risley. Chemical processes in the nuclear energy industry may be divided into two main groups. In the first group we can include the extraction of uranium from ore, the production of pure uranium metal and chemical compounds such as UO_2 and UF_6, and the production of special nuclear materials required as moderators or as cladding for fuel elements. These topics were covered in Sessions E.11 and E.12 at the Conference under the title "Production of Nuclear Materials." In the second group we can include the chemical processes involved in the separation of fission products, uranium and plutonium from irradiated fuel, and the production of concentrated fissile materials. These subjects were covered in Sessions C.17 and C.18 under the heading "Processing of Irradiated Fuels."

In addition, special attention was given to the problem of processing the concentrated fissile materials. Here, particularly, the designer must ensure that the quantities of fissile material present cannot produce a fission chain reaction, either under normal plant operating conditions or following a reasonably foreseeable series of errors.

These masterpieces of compression are being published in full in the *Journal of the British Nuclear Energy Conference*, April, 1959.

British Chemical Engineering
A HEYWOOD PUBLICATION

Passing of an Era

AS the era of the entrepreneur with his gift of intuition recedes, so too does the type of engineer upon whom he depended for his productive machinery pass from the scene: every design chemical engineer, especially the man with pre-war experience, is aware that even if in essence his functions are preserved, in many important details there have been great changes in his work. In pre-war days he would often find himself in a situation which called for a high degree of adaptability and versatility. He would, if trouble-shooting at a plant so required, don overalls and wield a wrench with the same ease as he used the slide-rule for his more conventional work. Neither was he averse to a spell upon the drawing-board if available draughting facilities proved inadequate for the job on hand. For a process plant, such was the state of knowledge, the basic flow sheet was often assembled by hook or by crook and by rule of thumb. The details of many pieces of equipment, their dimensions, shape and material were obtained, if not by intelligent guesswork and judgment, by methods of design which would be regarded today as crude over-simplifications. From free-hand sketches, a field in which he was adept, the drawings for plant fabrication would be made and his job would be to check them. His conception of the plant layout would be similarly consigned to the drawing-office where many hours would be spent arriving at what seemed to be the best all-round layout. To assist the chemical engineer of those days there was little more than the roots of the present-day technology. Only a handful of text-books were in existence to help him, and entire areas of the subject remained unexplored. The door was wide open, therefore, for the man of initiative with a strong intent to improve existing design methods and to invent new ones; and he had the advantage not always shared by his modern counterpart that he could check his calculations against the actual results his designs yielded. To summarise, the chemical engineer of that era was, as a rule, an all-rounder with a gift of improvisation who relied upon a combination of practical sense and empiricism to carry through much of his work. Such was the nature of this disappearing species, whose passing need not be regretted so long as efforts are made to ensure that his modern successor assimilates his good features.

His exit has been accelerated by profound changes in industry, of a kind particularly marked in the chemical and allied branches of industry. Foremost among them has been the continual expansion of the large corporations; at the same time many of the smaller firms have either been absorbed into the larger undertakings or else been eliminated altogether. These developments have undermined the material basis for the engineer of former days. Then, again, in the large corporation there is a considerable division of labour, a feature which does not leave untouched the various fields of engineering. The spheres of activity which the chemical engineer took for granted as his own in the old days he would find today shared out among many other engineers and he would at the same time encounter fields unrecognised in the pre-war era. Problems of material selection and protection, fluid flow, energy and mass transfer, automatic control and so forth, would each be a province for a single engineer or a group of engineers. As a consequence, the field for the individual engineer within the large corporation with its monolithic structure may seem far more restricted. There are risks in this state of affairs which some, but not all, leaders of industry recognise. There is the danger that the individuality and initiative of the engineer may be surrendered to the organisational pattern of the larger firm. If this prevails it is likely that the chemical engineer, with but one or two narrow fields in which to work, will feel impelled by frustration to seek other avenues for exercising and developing his talents. Primarily these are problems which managements must solve if they wish to avoid a turnover of staff.

Also exercising considerable pressure for change in the manner in which chemical engineers work is the totality of industrial problems requiring solution. If these, by their nature, permit very wide scope for technology, they demand at the same time exceptional knowledge and methods of approach, as well as the power to manipulate a mass of facts, before economical solutions can be obtained. In the sphere of nuclear energy, for example, despite some apparent freezing of design there is the whole question of fuel cycles, whether they should use natural or enriched fuels, or be solid or mobile, with the associated problems of reprocessing and waste disposal, all of which need exploration and applied chemical engineering.

Alongside the changes in industry and the pressure of industrial problems have been the developments in technology of the post-war period. This, too, has influenced considerably chemical engineering. The rise of automatic process control and process dynamics, the rapid growth of computer and simulation techniques and a far greater insight into economics are among the many factors which call for a chemical engineer differing from his predecessor of pre-war years. One might mention in passing the benefits available from the analogue computer alone, such as the design of chemical reactors, the study of catalyst regenerators, the solution of distillation problems, the simulation of process plants and a wide range of problems requiring the solution of systems of simultaneous linear or non-linear differential equations. With these new tools the modern engineer is able to solve problems far beyond the capability of pre-war chemical engineering, but although far better process design is now possible no one would claim that the job of the engineer has been made any easier. Today he finds he must be something of a specialist or at least have the capacity to specialise and at the same time strive to preserve the broadness of perspective of his predecessor. He is today passing through a rapidly changing but exhausting phase, a fact which top managements would do well to appreciate. At the end of it, if conscious guidance and suitable organisation prevail, we may see replacing the all-rounder of yesteryear a new type of engineer devoid of the limited vision of the specialist but able to exercise many of the functions of the latter.

66.045.1:620.191.2

Fig. 1. Some fouled heat-exchangers being prepared for cleaning at the B.P. Kent oil refinery. The analysis presented in this article offers a possibility of a substantial reduction in the number of such occurrences.

A THEORETICAL ANALYSIS OF THERMAL SURFACE FOULING*

A new approach to fouling offers the possibility of a more rational method of heat-exchanger design

by D. Q. KERN and R. E. SEATON

IN the design of heat-transfer equipment it is generally assumed that the apparatus will be placed on stream in a clean condition and that dirt will be deposited on the heat-transfer surface by the fluids interchanging heat. To compensate for the accumulative resistance of the dirt, two common procedures have been employed which provide extra surface beyond the requirement for clean operation: these are the fouling factor and the cleanliness factor. The cleanliness factor is a percentage allowance imposed on the clean overall coefficient and has been used particularly in the design of steam surface condensers in which the services are all very similar.

The fouling factor has been used extensively in the process industries. Even a cursory examination will indicate that it is not a reliable means for providing the extra surface and that increments of fouling factor, as generally introduced in design, can actually reduce the expected period of performance.

Among the more objectionable aspects of the fouling factor are the following: (a) The fouling factor employs the unit dimension of time but is only verbally identified with a period of time. In no way does it describe the performance of an apparatus during the interval from time zero, when it was clean, and the time when sufficient dirt will have deposited to prevent delivery of the rated heat load. (b) An exchanger becomes inoperative when the temperature drop through the dirt exceeds that for which extra surface was allowed. The temperature drop through the dirt is dependent not only upon the fouling factor, r_d, but also upon the heat flux, Q/A. Hence, (c) the same fouling factor can provide different periods of service for fluids of similar dirt characteristics but employed under different fluxes which result either from different temperature differences or heat-transfer coefficients. There is also no implied dimension by which two units of fouling factor produce twice or any multiple of the performance period of one unit. (d) An increment of fouling factor can actually reduce a period of service; for example, consider the case where a loose relationship has been established between fluid velocity and surface fouling. When the velocities of the fluids interchanging heat are increased, the surface fouling is reduced. Suppose an apparatus were designed to incorporate a given set of fouling factors and either the maximum practical number of tube passes or the minimum practical shell baffle spacing. If an alternate unit were designed with the same overall tube length, but for larger fouling factors on either or both of the streams, it would be necessary to reduce the linear velocity of one or both streams. The reduction in the fluid velocity or velocities could conceivably increase the opportunity for the heat-transfer surface to become fouled to such an

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* This article appears by permission of the A.I.Ch.E. and was presented as a paper to the annual meeting of the American Institute at Cincinnati, Ohio, December 7-10, 1958.

Symbols Used

A = heat-transfer surface based on tube OD, sq. ft;
a = exponent;
B = constant;
c = constant;
c' = dirt concentration consistent with K_1;
D = tube inside diameter, ft;
f = friction factor, dimensionless;
g = gravitational constant, ft/hr^2;
K_1, K_2 = constants;
K_f = BLASIUS constant;
L = total tube length, ft;
M, N = substitution terms;
P = pressure in pressure gradient, lb./sq. ft;
$\triangle P$ = pressure drop, lb./sq. ft;
$\triangle P_1^*, \triangle P_2^*$ = comparative values of the pressure drop, lb./sq. ft;
Q = heat flow, Btu/hr;
Q_θ = heat already delivered, Btu;
R = transient fouling resistance, hr × sq. ft × °F/Btu;
r_d = fouling factor expressed as a fixed number, hr × sq. ft × °F/Btu;
$\triangle t$ = temperature difference, °F;
U = overall heat transfer coefficient, Btu/hr × sq. ft × °F;
V = velocity, ft/hr;
W = constant weight flow, lb./hr;
x = thickness of a dirt film, ft; and
x_1^*, x_2^* = comparative values of the dirt film thickness, ft.

Greek

α = proportionality constant;
θ = time, hr;
μ = viscosity, lb./ft × hr;
ρ = density, lb./cu. ft; and
τ = shear stress, lb./sq. ft.

Subscripts

0 = time zero; and
θ = finite time.

Superscript

* = characteristic of the asymptote.

extent that the increase in surface would be more than offset. (e) There is no definitive relationship between the growth of a fouling factor and time; accordingly, in a new service there is no way to determine early in the operating period whether or not the anticipated fouling allowances were correct, and whether it might be necessary to go off-stream earlier than expected. (f) In design practice the allowable pressure drop for fluid circulation is often fixed at 10 psi per stream per exchanger. If relationships are conceded between dirt accumulation, pressure drop and the fluid velocity, it is inconceivable that two fluids having different dirt characteristics should comply with the same pressure drop allowance. The fact that one stream fouls more than the other suggests through fundamental economics that the dirtier stream be circulated more rapidly. If this is done, it may not deposit dirt any faster than the less dirty stream. (g) Lastly, the fouling factor has probably been responsible for the dearth of available information on the nature and mechanics of dirt deposition which, in turn, would enable the designer and operator to exercise control over its accumulation.

Approaches to Thermal Surface Fouling Transients

It is the object of this analysis to establish physical and mathematical relationships between an allowable pressure drop and the accumulation of dirt with time.

In the literature, the only mathematical postulation involving thermal surface fouling was presented by McCABE and ROBINSON.[1] They were interested in establishing transient equations for the build-up of scale inside the tubes of evaporators. They assumed that the accumulation of scale was proportional to the total quantity of heat already delivered by the evaporator from time zero when it was placed on stream. They show that the variation of the dirty overall film coefficient U_θ with time can be expressed by the equation:

$$\frac{1}{U_\theta^2} = \frac{1}{U_o^2} + (2\alpha A \triangle t)\theta \qquad \ldots.(1)$$

U_o is the clean overall coefficient at time zero, α is the proportionality constant relating the dirt R_θ at time θ to the heat already transmitted, Q_θ. A and $\triangle t$ are the surface and temperature difference respectively. Their approach employs a time independent constant temperature difference which occurs frequently in evaporation. In this case, two isothermal fluids interchange heat, while the gross quantity of heat exchanged per hour deteriorates with time through the scale build-up. Their analysis in the form in which they have developed it is not applicable when one or both of the fluids undergoes a change in sensible heat.

At the outset it appears desirable to define and distinguish between *dirt* and *scale* as used in this article. Dirt implies finely divided non-polar particles which are carried along by the fluid stream and which deposit uniformly upon tubular heat-transfer surfaces. We will assume that the particles have no particular attraction for each other or for the tube, adhering to each other and to the tube surface only by virtue of their irregular shapes. In the case of scale, there may be true crystal growth in which the forces binding adjacent crystals or adjacent portions of single crystals may be of a higher order of magnitude.

Here we are concerned with the simplest type of dirt deposition; namely, that occurring inside a tube of uniform diameter. The packing effect by which dirt may be bound more strongly at the inside diameter of the tube than at the inside diameter of the dirt has been omitted. It has been studied by the authors, but since it compounds one set of assumptions upon another, its presentation here appears premature. To lend generality to the analysis, the distinction between dirt deposition and scale need only be considered as a matter of degree, since scale build-up also shows the same kind of inverse rate of accumulation with changing fluid linear velocities.

The decreasing rate of dirt deposition with increasing fluid linear velocity suggests the influence of fluid shear as an agent for removing dirt at the fluid-dirt interface. Fouled exchangers can often be cleaned to some extent by temporarily increasing the velocity of the circulating fluid.

What attractions might exist between a non-polar particle and the wall of a tube are not readily explained, unless real particles are not truly non-polar. Certainly if there is an unexpected affinity by which a non-polar particle is attracted to the tube surface, it would appear that the unsuspected physico-chemical effect would exhaust itself once the minutest initial deposition had occurred, and the attraction would merely serve to start the process. The same condition would result if the fluid itself engaged in corrosive attack on the metal, thereby initiating an environment for interlinkage of particles.

The dirt accumulation may be regarded as the resultant of two simultaneous processes of deposition at right angles to the bulk fluid flow and removal by fluid shear in the direction of fluid flow, and a potential might be expressed for accumulation and another for removal.

The net accumulation can be expressed as a quotient with a deposition term in the numerator and a removal term in the denominator. It can also be expressed using

deposition as a series of terms, and removal as a series of terms, so that the net accumulation is obtained by subtraction. The use of difference terms has proved to be much more rewarding than quotients because of the tendency in the latter for variables to cancel out and lose identity as fluid dynamic entities.

Development of a Transient

Occasionally, a graph appears in the literature which shows the fouling of a particular piece of equipment with time. An example[3] for oil outside water-cooled tubes is replotted in Fig. 2, and it adds confirmation to the fact that the fouling resistance grows asymptotically with time. These curves can be approximated by a transient equation of the form:

$$R_\theta = R^* (1 - e^{-B\theta}) \qquad \ldots . (2)$$

R^* is the value of R_θ at the asymptote. As seen in Fig. 3, by increasing the value of B the form of the curve produced in Fig. 2 can be approximated.

The removal potential. A flowing fluid exerts a shear stress τ at a wall which can be related to the friction factor f. It will be assumed that the friction factor is constant and independent of the presence or quantity of dirt. The shear stress on the wall, dirty or clean, is readily shown to be related to the pressure gradient by

$$\tau = \left(\frac{dP}{dL}\right)\left(\frac{D}{4}\right) \qquad \ldots . (3)$$

where dP/dL is the pressure gradient and D the inside diameter of the tube. Also:

$$\frac{dP}{dL} = \frac{2fV^2\rho}{gD} \qquad \ldots . (4)$$

from which

$$\tau = \frac{2fV^2\rho}{4g} \qquad \ldots . (5)$$

If the dirt film is thin, V and f remain unchanged during the period in which the dirt accumulates. The deposition potential depends upon the form of the driving force. From Equation (5) it appears that if curves of the type shown in Figs. 2 and 3 are to be obtained, then the deposition term itself must impart the asymptotic inflection. This suggests a driving force equation of the form:

$$\text{Driving force} = ce^{-B\theta} \qquad \ldots . (6)$$

where c and B are constants. Combining Equations (4), (5) and (6), one obtains on integration:

$$R_\theta = \frac{4cg}{2fV^2\rho B}(1 - e^{-B\theta}) \qquad \ldots . (7)$$

While c and B are arbitrary, the influence of V is indicated.

Now consider the actual deposition and removal *quantities* separately and combine into a net *difference* or accumulation equation. To this end, assume that the rate of transport and deposition are constant with time. Of course, if the removal rate varies with time, so will the build-up rate and net build-up. The constant rate of deposition can be expressed by:

$$\text{Rate of deposition} = K_1 c' W \qquad \ldots . (8)$$

where K_1 is a proportionality constant, W is the constant weight flow of fluid, and c' its unit dirt content.

To permit an expression for the *rate* of removal, it is necessary to employ definitive assumptions. From among many corollary assumptions the following are helpful in arriving at an *average* rate of removal.

Assumptions: (1) removal is due to the shearing action of the stream at the surface of the dirt; (2) instead of being removed particle by particle, dirt is sheared off in chunks at random planes of weakness in the dirt; (3) planes of weakness are likely to occur at any depth.

Predicated upon these assumptions the average removal rate over the whole tube would be roughly proportional to the depth of dirt accumulated. Then we can express the removal rate in a form similar to Equation (8) for the rate of deposition.

$$\text{Rate of Removal} = K_2 \tau x_\theta \qquad \ldots . (9)$$

where K_2 is also arbitrary and x_θ is the thickness of the dirt. The change in the film thickness with time is then:

$$\frac{dx_\theta}{d\theta} = K_1 c' W - K_2 \tau x_\theta \qquad \ldots . (10)$$

If the thickness of the film as it grows affects appreciably the linear velocity and, hence, the shear stress, this variation may be included by introducing the BLASIUS equation:

$$f = \frac{K_f}{\mathrm{Re}^a} \qquad \ldots . (11)$$

where K_f is the BLASIUS constant, usually about 0.079, and a is a constant such that $0 \leq a \leq 0.25$. The Reynolds number for the fluid flowing in the constricted dirty tube may be written:

$$\mathrm{Re} = \frac{(D - 2x_\theta)V\rho}{\mu} \qquad \ldots . (12)$$

The velocity V is related to the weight flow W by:

$$V = \frac{W}{\rho \frac{\pi}{4}(D - 2x_\theta)^2} \qquad \ldots . (13)$$

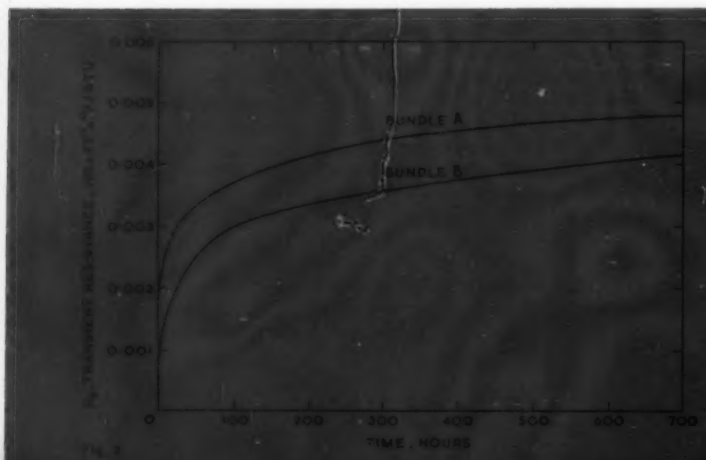
Combining Equations (5), (11) and (13) gives:

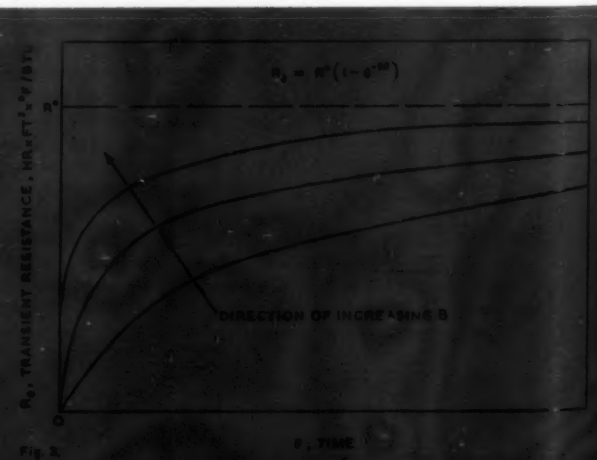
$$\tau = \frac{2^{(3-2a)}}{\pi^{(2-a)}} \cdot \frac{K_f}{g} \cdot \frac{W^{(2-a)}}{\rho} \cdot \frac{\mu^a}{(D - 2x_\theta)^{(4-a)}} \qquad \ldots . (14)$$

To obtain an equation for the fouling transient, combine Equations (10) and (14):

$$\frac{dx_\theta}{d\theta} = K_1 c' W - \frac{2^{(3-2a)}}{\pi^{(2-a)}} \cdot \frac{K_f K_2}{g} \frac{\mu^a W^{(2-a)}}{\rho} \frac{x_\theta}{(D - 2x_\theta)^{(4-a)}} \qquad \ldots . (15)$$

$$\text{Let } M = K_1 c' W; \; N = \frac{2^{(3-2a)}}{\pi^{(2-a)}} \cdot \frac{K_f K_2}{g} \frac{\mu^a W^{(2-a)}}{\rho}$$





Rearrange Equation (15) for integration:

$$\theta = \int_0^{x_\theta} \frac{dx_\theta}{M - N \cdot \dfrac{x_\theta}{(D-2x_\theta)^{(4-a)}}} \qquad \ldots.(16)$$

The integrand converges for $\left[\dfrac{N}{M} \cdot \dfrac{x_\theta}{(D-2x_\theta)^{(4-a)}}\right] < 1$ or the rate of deposition exceeds the rate of removal at all times. Rewriting Equation (16) one obtains:

$$\theta = \frac{1}{M}\int_0^{x_\theta} \left\{1 + \frac{N}{M}\cdot\frac{x_\theta}{(D-2x_\theta)^{(4-a)}} + \left[\frac{N}{M}\cdot\frac{x_\theta}{(D-2x_\theta)^{(4-a)}}\right]^2 \right. \qquad \ldots.(17)$$

$$\left. + \left[\frac{N}{M}\cdot\frac{x_\theta}{(D-2x_\theta)^{(4-a)}}\right]^3 + \ldots\ldots\ldots\ldots\right\} dx_\theta$$

The component parts of Equation (17) are shown in Fig. 4 with all constants arbitrary. Having obtained a relationship between weight flow, film thickness and time we can now proceed to a relationship between the film thickness and the pressure drop, $\triangle P$. Eliminating f in Equation (5) we have:

$$\triangle P = \frac{4L\tau}{(D-2x_\theta)} \qquad \ldots.(18)$$

and

$$\frac{d(\triangle P)}{d\theta} = \frac{4L}{(D-2x_\theta)}\left(\frac{d\tau}{d\theta}\right) \qquad \ldots.(19)$$

Combining Equations (18) and (19):

$$\frac{d(\triangle P)}{d\theta} = \frac{4L}{(D-2x_\theta)}\left(\frac{d\tau}{dx_\theta}\right)\left(\frac{dx_\theta}{d\theta}\right) \qquad \ldots.(20)$$

$\dfrac{dx_\theta}{d\theta}$ in Equation (20) is given by Equation (10). Differentiating Equation (14) with respect to x_θ yields $\dfrac{d\tau}{dx_\theta}$. The result when substituted in Equation (20) then becomes:

$$\frac{d(\triangle P)}{d\theta} = \frac{4L}{(D-2x_\theta)}\left\{\frac{2^{(4-2a)}\,(4-a)}{\pi^{(2-a)}}\cdot\frac{K_f}{g}\cdot\frac{\mu^a}{\rho}\cdot\frac{W^{(2-a)}}{(D-2x_\theta)^{(5-a)}}\right\}$$

$$\left\{K_1 c' W - \frac{2^{(3-2a)}}{\pi^{(2-a)}}\cdot\frac{K_f K_2}{g}\cdot\frac{\mu^a W^{(2-a)}}{\rho}\cdot\frac{x_\theta}{(D-2x_\theta)^{(4-a)}}\right\} \qquad \ldots.(21)$$

This general case is integrable by computer. However, of greater interest is the particular solution relating the thickness of the dirt at any asymptotic deposition and the pressure drop required to attain it. From Equation (21) it is apparent that a different asymptote can exist for each allowable pressure drop. The matter now becomes one of determining how much energy is required to reduce the asymptotic thickness of the dirt to a point where it becomes a permanently tolerable resistance to the transmission of heat. If the dirt has no packing effect, the value of the transient resistance, R_θ, is directly related to the transient dirt thickness x_θ, by the constant value of the thermal conductivity of the dirt.

An asterisk will be used to indicate the characteristics of the variables at the asymptote. Referring to Fig. 3, consider now the energy requirements to reduce the height of x_θ so that apparatus may operate continuously while being in a dirty state. The asymptotic dirt film thickness x^* in Equation (21) is given by

$$\frac{x_\theta^*}{(D-2x_\theta^*)^{(4-a)}} = \frac{M}{N} \qquad \ldots.(22)$$

The value of the pressure drop at the asymptote in Fig. 3 is given by

$$\triangle P_\theta^* = \frac{4L\tau^*}{(D-2x_\theta^*)} \qquad \ldots.(23)$$

From Equation (14):

$$\tau_\theta^* = \frac{N}{K_2(D-2x_\theta^*)^{(4-a)}} \qquad \ldots.(24)$$

Combining Equations (22) and (24):

$$\triangle P_\theta^* = \frac{4LN}{K_2(D-2x_\theta^*)^{(5-a)}} \qquad \ldots.(25)$$

Combining Equations (22) and (25):

$$\triangle P\theta^* = \frac{4LM}{K_2(D-2x_\theta^*)x_\theta^*} \qquad \ldots.(26)$$

Replacing M by its components shows the influence of tube diameter on the ability of the apparatus to operate indefinitely in the dirty asymptotic condition.

$$\triangle P_\theta^* = \frac{4LK_1 c' W}{K_2(D-2x_\theta^*)x_\theta^*} \qquad \ldots.(27)$$

and

$$D = \frac{4LK_1 c' W}{K_2 \triangle P_\theta^* x_\theta^*} + 2x_\theta^* \qquad \ldots.(28)$$

From Equations (14) and (24):

$$\triangle P_\theta^* = \frac{2^{(5-a)} K_f L W^{(2-a)} \mu^a}{\pi^{(2-a)}\, g\, \rho (D-2x_\theta^*)^{(5-a)}} \qquad \ldots.(29)$$

Eliminating $(D-2x_\theta^*)$ between Equations (27) and (29) and taking $a = 0$ we obtain:

$$x_\theta^* = \frac{2K_1 c'}{K_2}\left(\frac{\pi^2 g \rho L^4 W^3}{K_f(\triangle P_\theta^*)^4}\right)^{\frac{1}{5}} \qquad \ldots.(30)$$

$\dfrac{K_1 c'}{K_2}$ characterises the fouling qualities of the fluid and should remain unchanged. For their evaluation one need only refer to the operating charts for similar services and obtain the initial stream temperature and the current or final stream temperatures and the time elapsed. The remaining resolutions can be made by permutation.

One can estimate the influence of the variables by taking the ratio of the asymptote for the same fluid under two different operating conditions. The ratio becomes:

$$\frac{(x_\theta^*)_2}{(x_\theta^*)_1} = \frac{\left[\dfrac{L^4 W^3}{(\triangle P_\theta^*)}\right]_2^{\frac{1}{5}}}{\left[\dfrac{L^4 W^3}{(\triangle P\theta^*)}\right]_1^{\frac{1}{5}}} = \left(\frac{L_2}{L_1}\right)^{0.8}\left(\frac{(\triangle P_\theta^*)_1}{(\triangle P_\theta^*)_2}\right)^{0.8}\left(\frac{W_2}{W_1}\right)^{0.6} \qquad \ldots.(31)$$

It will be seen from Equation (31) that a favourable inverse relationship exists between dirt deposition and the pressure drop required to suppress it.

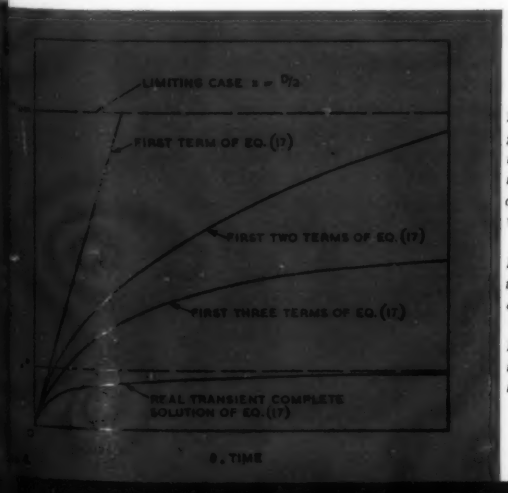

LIMITING CASE
FIRST TERM OF EQ. (17)
FIRST TWO TERMS OF EQ. (17)
FIRST THREE TERMS OF EQ. (17)
REAL TRANSIENT COMPLETE SOLUTION OF EQ. (17)
θ, TIME

Fig. 2. Typical dirt growth curves based upon the observations of Katz and others[2] for oil outside water-cooled tubes.

Fig. 3. Plot of Equation (2) with arbitrary constants.

Fig. 4. Plot of Equation (17) with arbitrary constants.

Numerical Examples

In a recent article the authors[3] described a common occurrence in plant operation. The figures are somewhat exaggerated to demonstrate the point. A light-ends overhead condenser condenses a vapour from 130° to 100°F using cooling tower or surface water operating from 85°

to 100°F. A substantial part of the condensate returns to the column as reflux. A cold climatic spell develops, dropping the inlet temperature of the water to 55°F. Assuming the same approach as before, the outlet temperature of the condensate drops from 100° to 70°F. The demand on the reboiler utilities increases while the separation of the overhead product falls off because the subcooled condensate nullifies several of the upper trays of the column. To bring the condensate temperature back to 100°F. the water is throttled to provide a range from 55° to 100°F.

Previously, with a 15° range the water flowed at a design linear velocity of, say, 3 fps. With a range of 45°F in cold weather the linear velocity has been reduced to 1 fps. After a relatively brief period of operation under these conditions the condensate rises above the 100°F outlet. A gradual increase in the water flow rate fails to produce any visible effect. Why will a condenser which performed satisfactorily in the summertime on hot water fail to perform in the wintertime when there is an abundance of cold water? The answer obviously is dirt. In the light of Equation (31), if the condenser were performing at 3 fps at an asymptotic dirt level such that it created no cleaning problem, what quantitative effect did throttling have?

The length of path remains the same and, using the subscript 1 for the original condition, $L_2 = L_1$. Since flow has been cut to one-third, the pressure drop at the asymptote has dropped approximately to one-tenth so that $\triangle P_1^* / \triangle P_2^* = 10$. The amount of dirt brought into the system is represented by the weight flows and so $W_1/W_2 = \frac{1}{3}$. Equation (31) then becomes:

$$x_2^* = \left(\frac{1}{1}\right)^{0.8} \left(\frac{10}{1}\right)^{0.8} \left(\frac{1}{3}\right)^{0.6} = 3{,}28\ x_1^*$$

In other words, the thickness of the dirt under asymptotic conditions has increased 328%. If the water and condensation coefficients are relatively high, the throttling action can make the asymptotic dirt layer the controlling resistance.

Consider yet another case. Preliminary design of a condenser with fixed tube length and two tube passes indicated a computed water pressure drop of 1.75 psi against an allowable pressure drop of 10 psi. If four passes were employed instead of two, the pressure drop would be approximately 14 psi. What would be the result if the designer exceeded the allowable pressure drop? $W_2 = W_1$, $L_2/L_1 = 2$ and $\triangle P_1^* / \triangle P_2^* = \frac{1}{4}$. For this case $x_2^* = 0.33\ x_1^*$ or by pressurising for only 4 extra psi (which are usually available anyway) the asymptotic dirt level would have been only one-third as great.

While the foregoing numbers look promising, one must consider the assumptions used in the derivation and their limitations; also, the fact that the analysis was derived only for the tube side of the exchanger.

Shell side fouling might be treated similarly. This is no worse than the usual methods of computing shell side coefficients, since most shell side equations are manipulations of an equation obtained by dimensional analysis on the tube side. There also seems to be little reason for shell or tube side heat transfer to be calculated on the basis of empirics instead of theoretical fluid dynamics. Then the coefficient and its dirt could be solved for simultaneously.

Second, while the cost of suppressing the growth of dirt is not excessive for incompressible fluids where a high static head can be obtained relatively cheaply, this is not true for compressible fluids; fortunately, most compressible fluids do not foul seriously. Third, there is also the practical limitation that the velocity of the fluid cannot be so high that it causes incipient erosion of parts of the apparatus. Fourth, if the apparatus will corrode out in a shorter period of time, there is no reason to extend costs by incorporating dirt suppression.

Two types of service can be distinguished: those in which the dirt can be suppressed economically through the use of static head and those in which it cannot be suppressed economically. The latter class simply establishes at the outset of designing a plant the requirement for partial or total stand-by in certain services. The cost of such a plant need not be any greater than one of conventional stop-and-go design. By raising the entire magnitude of design pressure drops, the heat-transfer coefficients are also increased, yielding smaller exchangers to offset the expense of stand-bys.

There appears to be a definite reward in the abandonment of the common design practice of using fixed pressure drops and allowing extra surface by means of the fouling factor. Such apparatuses possess the inherent requirement of periodic removal from service for cleaning. The rational approach would be to design apparatus on the basis of the transient so that it could always operate dirty with a tolerable asymptotic thickness of dirt and never get any dirtier by virtue of the fluid shear on the surface. It is not within the scope of this paper to establish the method for designing the equipment employing the transient. In such a method the economically allowable pressure drop becomes the dependent variable.

Fig. 5. Silt deposit from Thames River water of stabiliser overhead condenser channel end. (Photo: Mobil Oil Co.)

ACKNOWLEDGMENT

The authors wish to acknowledge the generosity of the Wolverine Tube Division of Calumet & Hecla Inc., sponsors of the project, for permission to publish this extract.

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REDUCING TUBULAR EXCHANGER COSTS

Thermal design is not the only source of economy. Mechanical features, materials of construction and tube plate thicknesses also deserve attention

THIS subject does not receive the attention its importance deserves in the literature on heat exchange, although it is evident that conventional designs are often needlessly expensive. Elaborate mechanical designs and standardisation of design for the purpose of interchangeability have been recently criticised by KERN and SEATON[1] as generally uneconomic and in conflict with the sound design philosophy of buying only the equipment that is really necessary and at the lowest cost compatible with durability and maintenance. In material selection, another field of error for designers, the authors drew attention to the hazards of relying closely upon corrosion tables. Indeed, they point out that in a corrosion test vessel the temperature reported is that of the bath, whereas in an exchanger the metal surface may be very much higher than the corrosive solution which, in any case, is fresh. Where there is little experience of a corrosive material it is recommended that the designer selects the cheapest material of construction showing reasonable corrosion resistance. Another useful point is that with water-cooled equipment to specify a minimum allowable velocity of water and a maximum water outlet temperature is not an insurance against corrosion of steel or of copper alloys by water; moreover unusual metal combinations for which there is no past operating experience are to be avoided.

Alternatives to certain types of construction, such as the floating head, removable-tube-bundle arrangement, are considered. Unless some means such as mechanical scraping is required for cleaning the tube bundle, the use of such a form of construction is unjustified, especially with the development of chemical means of cleaning. An alternative to the floating-head type is the U-tube exchanger, although the removal of deposits which tend to settle in the bends is, however, a serious disadvantage. Fixed-tube-plate designs are adequate if the differential expansion between shell and tubes is limited. There are precautions to observe in their use; for example, if steam is the shell fluid and an organic liquid is passing through the tubes, the differential expansion may be small. But if the fluids are reversed and steam is passed through the tubes, the shell may operate cold and the tubes hot, so that the differential expansion will be much greater. To be safe the stress imposed by differential expansion should not exceed 9000 psi, and for a fixed-tube-plate exchanger 16 ft long this figure is not likely to be exceeded if the log. mean temperature difference is less than 100°F.

Some example of cost-saving elements in design are illustrated by KERN and SEATON but most of them are not widely used. The two-part shell with spring-sealed longitudinal baffle avoids the split floating head with the baffle welded to the shell—an extremely expensive form of construction. The one-shell pass, one-tube pass, floating-head exchanger with a nozzle from the internal header-box passing through a packed gland in the outer header-box is another type deserving wider use, but objections have been levelled at the use of the gland, most of which the authors overcome by means of a bellows joint.

Some of the fallacies attached to the use of fouling factors, the question of how much heat is worth recovering in an exchanger, and the merits and demerits of excess capacity provision are also examined by the authors (see also page 258 of this issue).

Another aspect of design with an important bearing upon the cost of heat exchangers is the tube plate thickness, and to obtain cheaper designs it has been proposed that allowance should be made for the supporting effect of the tubes themselves. Such proposals were made some years ago by MILLER[2] and useful design data since then have been provided more recently by DUNCAN.[3]

In a discussion of MILLER'S original method of estimating tube plate thickness, which treats the tubes as an elastic foundation for the tube plate, thicknesses for a number of examples were worked out by means of MILLER'S method. These results were compared with the thicknesses obtained by the TEMA standards. For example, a tube plate of 10 sq ft, according to TEMA standards, would require a 6-in. thickness, whereas with MILLER'S method 2½ in. only would be required, representing a saving of 7 tons of material and 350 ft of tube plate drilling.

GALLETLY and GARBETT[4] extend MILLER'S method and repeat the calculation for an end-clamped tube plate and obtain a thickness of 4.7 in. MILLER, incidentally, reduced the general problem to some simple formulæ and graphs. GALLETLY and GARBETT suggest a method for taking account of an effect which MILLER did not allow for in his original treatment of the subject—the bowing of the tubes. This may occur when the tube-side pressure is greater than the shell-side pressure, in which case the majority of the tubes will be in compression. If the shell-side pressure is the greater, then the tubes adjacent to the shell will be in compression; but of the two cases the former is the more serious and results in a reduction of the elastic support provided by the tubes. GALLETLY and GARBETT put forward an approximate solution which is satisfactory where the compressive loads on the tube are not close to the buckling load as determined by the Euler formula. The tube-plate thickness obtained by MILLER'S method is multiplied by a readily calculated factor, which is the ratio of support given by an imperfect tube to the support given by a perfect tube. The discussion concludes with a word of caution. Further work is necessary upon the effect of such variables in heat exchanger geometry as tube diameter, pitch as well as bowing, before the method can be used with complete confidence.

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LIQUID PHASE RESISTANCE IN WATER COOLING

A liquid film resistance is shown to exist, but is shown to be negligible for practical design purposes of direct contact coolers

by G. CRIBB

IN the November, 1958, issue of this journal MR. JACKSON[1] discussed the existence or otherwise of a liquid-film resistance to heat transfer in water cooling in the light of recent Soviet publications. He states that these publications claim that there is theoretical and experimental evidence for assuming the liquid film resistance to be negligible and they criticise the work of MCADAMS[2] *et al.* The existence of an appreciable liquid-film resistance would be very significant in the design of washer-coolers in which gas is cooled by direct contact with water, since in some of the new processes of gas manufacture saturation temperatures as high as 190°F are experienced. With this in mind an attempt was made to assess the liquid-film resistance in an experimental cooling tower in which mass-transfer coefficients were being determined for stacked 4-in. ceramic rings.

If the effect of liquid-film resistance was as great as claimed by MCADAMS, then for a given water and air rate it should be possible to observe variations in the overall gas phase mass-transfer coefficient with inlet water temperature.

Using the nomenclature of MICKLEY,[3] the following equations may be written down.

$$G\,di_G = K_G a\,(i_L - i_G)\,dZ \qquad \ldots.(1)$$

$$K_G\,(i_L - i_G) = k_G\,(i_i - i_G) = h_L\,(t_L - t_i) \qquad \ldots.(2)$$

$$h_L\,(t_L - t_i) = \frac{h_L}{m}\,(i_L - i_i) \qquad \ldots.(3)$$

where $m = (i_L - i_i)/(t_L - t_i)$.

$$\frac{1}{K_G} = \frac{a}{G}\frac{dZ}{di_G}(i_L - i_G) = \frac{a}{G}\cdot\frac{dZ}{di_G}((i_i - i_G) + (i_L - i_i))$$

$$= \frac{1}{k_G} + \frac{m}{h_L} \qquad \ldots.(4)$$

$$\frac{aZ}{G} = \frac{1}{k_G}\int\frac{di_G}{(i_L - i_G)} + \frac{1}{h_L}\int\frac{m\,di_G}{(i_L - i_G)} \qquad \ldots.(5)$$

The last equation may be written in the form:

$$\frac{1}{K_G} = \frac{1}{k_G} + \frac{\overline{m}}{h_L} \qquad \ldots.(6)$$

where $\overline{m} = \int\frac{m\,di_G}{(i_L - i_G)} \div \int\frac{di_G}{(i_L - i_G)}$.

Symbols Used

D = diffusion coefficient, ft²/hr;
G = mass flow of dry air, lb./ft² hr;
K = overall enthalpy transfer coefficient, Btu/ft² hr(Btu/lb.);
P = total pressure, atm;
Z = height of packing, ft;
a = specific surface of packing, ft²/ft³;
c = specific heat of water, Btu/lb. °F;
h = film heat transfer coefficient, Btu/ft² hr °F;
i = enthalpy, Btu/lb.;
k = film enthalpy or mass-transfer coefficient, Btu/ft² hr(Btu/lb.) or lb./ft² hr (lb./lb.);
k = thermal conductivity, Btu/ft² hr (°F/ft);
m = slope of chord on enthalpy saturation line, Btu/lb. °F;
p = partial pressure of diffusing gas, atm;
s = rate of surface renewal, hr⁻¹;
t = temperature, °F;
α = correction factor for humidity; and
ρ = density, lb./ft.³

Subscripts

G = bulk gas condition;
i = interface condition; and
L = bulk liquid condition.

It will be observed from Equation (6) that if k_G is assumed to be constant, K_G can only be constant if $\overline{m}$ is constant or h_L is infinite. As m is the slope of a chord on the saturation line, $\overline{m}$ can only be constant if the tower is operating over the same temperature range. In order to obtain different values of $\overline{m}$, the tower was operated at three different inlet water temperatures on a given day over a period when the wet-bulb temperature remained reasonably constant. For each set of three tests the air and water rates were kept constant. The tests were conducted in the open and there was some maldistribution of the air resulting in unsatisfactory heat balances. For this reason, the results were considered as preliminary and it was intended to repeat the experiments at a later date under closer control. In view of the points raised by MR. JACKSON, however, it is interesting to observe the trend indicated by the results obtained to date. The upper and

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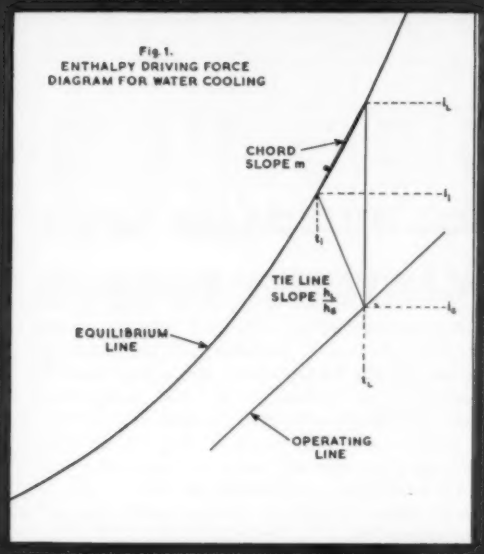

Fig. 1.
ENTHALPY DRIVING FORCE DIAGRAM FOR WATER COOLING

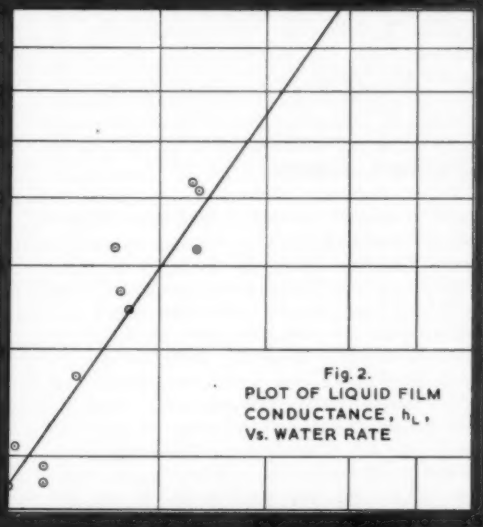

Fig. 2.
PLOT OF LIQUID FILM CONDUCTANCE, h_L, Vs. WATER RATE

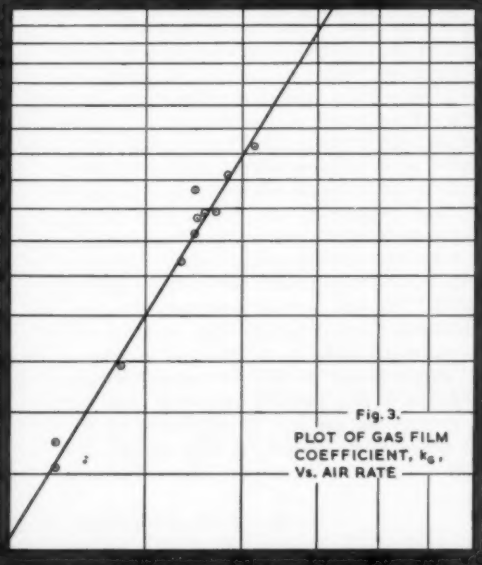

Fig. 3.
PLOT OF GAS FILM COEFFICIENT, k_G, Vs. AIR RATE

lower inlet water temperatures were approx. 110°F and 80°F respectively for most of the sets of tests and the K_G values at the higher inlet temperature were about 10% below those at the lower temperature. Mass-transfer coefficients should increase with temperature, but to counter this there is an error due to using humidity as the driving force for mass transfer, which is the basis of the enthalpy driving force method. It has been shown previously[4] that the true potential for mass transfer is αH, where α is given by $\left(\ln \frac{P}{P-p}\right) \div \left(\frac{p}{P-p}\right)$, α varies from 0.991 at 60°F to 0.895 at 140°F. Thus the true driving force is less than the humidity driving force. The employment of an enthalpy driving force will result in coefficients which are too low, the error increasing with temperature. It is estimated, however, that the error is about 3% for the high-temperature runs and 2% for the low-temperature runs, so the decrease in K_G from this source is about 1%. If it is assumed that the remainder of the variation in K_G is due to liquid-film resistance, values of the tie-line slope h_L/k_G may be determined. McAdams determined these graphically by trial and error, adjusting the tie slopes until the k_G values so obtained agreed with each other. This method is laborious and a rapid analytical method was sought. An exact value cannot be assigned to m unless the interface temperature is known, but at 110°F the difference in m is only 10% whether $(t_L - t_i)$ be 10°F or 1°F. As an approximation, therefore, values of m corresponding to a 1°F chord on the saturation line may be employed and values of m calculated. The reciprocal of K_G, corrected for the estimated error in the mean driving force, is plotted against $\overline{m}$ and the best straight line through the points is drawn by the method of least squares. The form of Equation (6) is such that the slope of the line is $1/h_L$ and the intercept $1/k_G$. The values so obtained are given in Table 1 and plotted in Figs. 2 and 3.

If greater accuracy is required and justified, a correction to the value of m may be made at this stage, since from Equation (2) $(t_L - t_i)$ is equal to $K_G\,(i_L - i_G)/h_L$. The correction factors may be plotted as a function of $(t_L - t_i)$ and the water temperature t_L.

The outstanding feature of these results is the very high velocity exponent for k_G and h_L, the value being about 1.5 in each case. This fact certainly requires further confirmation. Exponents as high as 1.36 for h_L are reported by Inazumi,[5] who analysed the data of Simpson and Sherwood[6] for Redwood slats. The h_L values range from 140 to just over 300 Btu/ft² hr °F compared with McAdams values of about 25 to 90 based on a specific surface (a) of 56 ft²/ft³ for 1 in. Raschig rings. However, as Jackson points out, McAdams worked well below the M.W.R. which is about 3000 lb./ft² hr for this packing. For 4-in. ceramic rings stacked in a square off-set arrangement a M.W.R. of 1340 lb./ft² hr is required according to Jackson. The wetting rates employed in the tests were therefore in the vicinity of the M.W.R. and adequate wetting of the packing may be assumed.

In Mr. Jackson's discussion, the probability is questioned of the existence of liquid-film coefficients of the order obtained by McAdams and the values of $t_L - t_i$ implied. Mention is made of the repeated mixing of the water and the consequent reduction of the liquid phase resistance to zero at each mixing. This physical picture is the basis of the surface renewal theory of Danckwerts[7] for mass-transfer in the liquid film. For purely physical absorption

$$k_L = \sqrt{DS}$$

where k_L is the liquid film coefficient (ft/hr);
D is the diffusion coefficient (ft²/hr); and
S is the rate of surface renewal (hr⁻¹).

TABLE 1

Test	1	2	3	4	5	6	7	8	9	10	11
Air rate lb./ft.²hr.	1740	1920	1850	1670	1790	1730	2080	1750	1150	1150	1400
k_G Btu/ft²hr (Btu/lb.)	58·3	61·2	54·8	47·0	54·3	51·2	66·7	53·9	27·5	25·7	34·7
Water rate, lb./ft²hr.	1110	1110	1200	1330	1660	1660	1630	1380	1350	1020	1000
h_L, Btu/ft²hr°F	140	147	186	263	261	307	314	221	234	154	138
h_L/k_G	2·4	2·4	3·4	5·6	4·8	6·0	4·7	4·1	8·5	6·0	4 0

For the absorption of gases, such as oxygen in water, k_L values are of the order of 1 ft/hr. To take a specific example for 1-in. Raschig rings at the M.W.R., the data of MOLSTAD *et al.*[8] give 0.93 ft/hr. If an analogy may be drawn between heat and mass transfer in the liquid film, then the diffusion coefficient D may be replaced by a group comprising the thermal properties of water, namely k'/ρ which also has the units ft²/hr. For water at 25°C the group has the value 0.347/62.3 or 0.00556 ft²/hr compared with diffusion coefficient for oxygen in water of 8.1×10^{-5} ft²/hr. The ratio yields an equivalent h_L of 8.3 ft²/hr which, when multiplied by $c\rho$, corresponds to 520 Btu/ft² hr °F. This is put forward as a possible theoretical explanation for a liquid-phase resistance of the order found experimentally. Further experimental evidence for the existence of a liquid-phase resistance in cooling towers is the work of KELLY and SWENSON[9] on splash packings. Fig. 4 of their paper indicates a 10% reduction in N.T.U. with increase in inlet water temperature from 100 to 150°F. The conclusion is, therefore, that although there is evidence of a resistance to heat transfer in the liquid phase in cooling towers, for practical design purposes it may be ignored. In washer-coolers the water loadings are ten times the M.W.R. and as the gas temperatures are higher than the water temperatures the increase in K_G with temperature and mass flow throughout the tower is appreciable. These two factors explain why the values of the overall mass-transfer coefficient K_G, obtained on a washer-cooler cooling gas from a saturation temperature of 190°F, compare favourably with those obtained for coolers handling gas at lower inlet temperatures.

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Mechanical Energy from Liquefied Gases

THE recent delivery of liquefied methane from Venezuela to this country and its storage on the Isle of Canvey in readiness for conversion to gas to supplement the coal-derived gas supplies of the North Thames Gas Board is an example of the ever-growing importance of liquefied gases. However, the loss of the available refrigeration in the liquid gas when the latter is vaporised into the distribution pipelines is a major disadvantage of schemes at present contemplated or in operation.

Taking as an example methane supplied as a gas at a pressure of 100 psig, the usual practice is to take the liquid from storage to 100 psig by means of a pump and to convey it to an exchanger, wherein it is vaporised and warmed to 15°C. If the heat required for this purpose is obtained from the natural surroundings or a source of waste heat, the sole energy requirement is for pumping the liquid from atmospheric pressure to 100 psig. Allowing a 50% margin over the theoretical power requirement, power consumption is 0.6 K cal/kg methane, and the heat extracted from the source cannot exceed that required for evaporating and superheating the methane.

A method of recovering a high proportion of the energy represented by the refrigeration originally required to liquefy any gas which in the liquid state has a low boiling point has been worked out by T. J. WEBSTER of the British Oxygen Co.* In this method, instead of vaporising the liquid at the delivery pressure of the gas, a much higher pressure is used and the gas is allowed to perform useful work by expansion in an engine. In the case of methane, the liquid in the first place is pumped to a pressure considerably in excess of the required gas delivery pressure which may be 100 psig, is then vaporised and the resultant gas allowed to expand to 100 psig in an expansion engine. This results in a gain of mechanical energy, since the energy produced by expanding the gas from 1000 to 100 psig will be much greater than the energy required to raise the liquid to 1000 psig. However, since cooling is produced by the expansion additional heat will have to be provided to raise the gas to 15°C, and for this purpose another exchanger is necessary downstream of the expansion engine. The theoretical energy gain from this expansion, which in practice will be predominantly adiabatic, is 56 K cal/kg methane. Assuming that mechanical inefficiency cancels out any gain of energy arising from the deviation from the adiabatic to isothermal expansion, this figure is a fair representation of energy gain.

For pumping the liquid methane to 1000 psig, making the 50% allowance as previously, 6 K cal/kg of methane are required. Hence the net gain is 50 K cal/kg of methane and since in the conventional procedure 0.6 K cal/kg of methane are necessary the gain to be expected is slightly greater than the figure of 50 K cal/kg. This would mean for a rate of methane evaporation of two tons per hour a net gain of more than 118 kW.

The mechanical energy thus generated may be used in a number of ways. In one arrangement gas produced by heat in-leak to the storage tank is conveyed to a compressor driven by the expansion machine. The compressor raises the vapour to 100 psig and feeds it into the mainstream of methane gas leaving the second exchanger. This version of the basic process, assuming a 60% adiabatic efficiency for the compressor and an evaporation of two tons an hour of methane, would be capable of compressing 113,000 cu. ft/hr of methane gas at −161°C (the boiling point of methane at 1 atm.) from atmospheric pressure to 100 psig. With the two tons evaporated by the heat exchanger this would amount to 219,000 cu. ft of methane at 100 psi compressed without any power cost whatsoever.

In other applications of this system the expansion machine could be a free piston-compressor used both to expand the compressed gas and to compress the gas produced from evaporation caused by heat in-leak into the storage vessel.

* British Patent 808,535.

661.183.1:541.183.1

NEW SELECTIVE SORBENTS: POROUS CRYSTALS AS MOLECULAR FILTERS*

The structure and action of new selective sorbents are reviewed and possibilities are indicated for their large-scale use

by R. M. BARRER, D.Sc. (N.Z.), Sc.D. (Cantab.), F.R.S.

1. Introduction

MOLECULAR sieve action may manifest itself in two ways: first, by selective transmission through continuous membranes, and, second, by selective occlusion through the surface of a porous crystal into the body of the crystal—the process discussed in this paper. Excellent molecular sieve sorbents are found in the zeolite family of minerals. Many can now be synthesised and several synthetic zeolites can be obtained commercially.

About 1938 the writer was led, through considering the rather scanty information then available on zeolite structures, to the view that zeolites should be able to function as perfectly selective molecular sieve sorbents. On the one hand, when their natural crystal water was removed by heat and evacuation some of these crystals developed a sorptive capacity which rivalled that of the best gas sorbing charcoals. On the other hand, they were porous crystals, the pore systems of which consisted only of channels of molecular dimensions, these dimensions being quite precise and controlled as accurately as the positions of the lattice atoms surrounding them. Unlike the irregular pore size distributions found in charcoals, silica gels, alumina-silica gels, activated alumina or fuller's earth, the channels and cavities in a given zeolite were thus tailored all to one set of dimensions. These dimensions could vary somewhat along the length of a channel, but the periodicity was perfectly regular. Molecules which were of the wrong shape and size would be totally unable to penetrate into the crystals; others of suitable shape, or smaller, might penetrate readily, and would then under appropriate conditions of pressure and temperature saturate the intracrystalline free volume of the porous crystals. Thus it should be possible to introduce a hitherto unattained selectivity into sorption processes.

In a series of researches these predictions were then fully verified, and naturally occurring and also one or two synthetic zeolites were used to separate a wide variety of mixtures.[1, 2, 3, 4, 5, 6, 7] The extraordinary versatility of these porous crystals has been extended by their synthesis,[8, 9, 10, 11, 12, 13, 14, 15, 16] and by making a number of them commercially available for industrial processes.[17] In this paper the synthesis of porous crystals will not, however, be discussed.

2. Structural Aspects

A considerable number of alumino-silicates are known which possess open or porous anionic frameworks. Some of these have intracrystalline cavities and channels filled with water (e.g., the zeolites, fibrous clays and montmorillonites) while some have these cavities filled with less volatile constituents such as salts (e.g., sodalite-nosean felspathoids, cancrinite, scapolites). Certain structures have both water and non-volatile constituents together in the porous alumino-silicate framework (e.g., basic sodalites, noseans and cancrinites).[11] These crystals do not develop their spectacular gas-sorbing and molecular sieve behaviour unless the water and salts can be removed without collapse of the surrounding framework. Some of the zeolites do possess the necessary three-dimensional stability and become valuable sorbents of unique selectivity when the intracrystalline water is evacuated. It is more difficult to remove inorganic salts when these fill the pores of the crystals. However, by progressive hydrothermal extraction a zeolitic molecular sieve sorbent was produced from a synthetic barium alumino-silicate in which $BaCl_2$ was a filler of intracrystalline cavities and channels.[7, 8]

Among crystals with porous alumino-silicate frameworks, structures have now been suggested for analcite,[18] fibrous zeolites of the natrolite family,[19] faujasite,[20] Linde sieve A,[21] erionite,[22] chabazite,[23] gmelinite[23] and harmotome-type zeolites.[24] Structures have also been given[25] for the felspathoids nosean, sodalite and ultramarine, and for cancrinite and the scapolites. Some of these structures can be easily visualised as the result of stacking together various polyhedral units in appropriate co-ordination and in different ways. These polyhedra are themselves composed of clusters of SiO_4 and AlO_4 tetrahedra. For example, eight tetrahedra can give a cubic unit; twelve tetrahedra can give a hexagonal prism; and twenty-four tetrahedra a cubo-octahedron (Fig. 1). Polyhedra such as the cubo-octahedron already contain considerable open space. Fig. 2 gives a portion of a structure based upon an arrangement of hexagonal prisms, which is characteristic of chabazite.[23] The interesting point emerges that stacking of hexagonal prisms in this way leaves large cavities in the structure. In chabazite each such cavity is

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* Article received September 10, 1958.

capped at top and bottom by a hexagonal prism and has six rings of eight tetrahedra acting as "windows" leading into six other large cavities. The "free"* diameters of these windows are about 3.9Å; the free length of the large cavity is ~11Å, and its free diameter normal to its length varies between 7.6 and 6.6Å.† Each large cavity contains in the hydrated zeolite 12 to 14 water molecules and cations sufficient in number to neutralise the anionic framework charge.

Large as are the cavities in this structure, they are smaller than the biggest cavities in Linde sieve A (Fig. 3).[21] This structure can be visualised as formed by stacking cubo-octahedral units in six-fold co-ordination, by four oxygen bridges from each of the six four-membered rings of central cubo-octahedron to one of the four-membered rings of six other such octahedra. This mode of linking produces also the cubic anionic units, and additional very large cavities, regular in shape and having a free diameter of ~11.8Å. Six eight-membered ring windows of free diameter ~4.2Å give ready access to each of six other very large cages, so that the crystal is very open. Each large cavity may contain 27-28 water molecules.

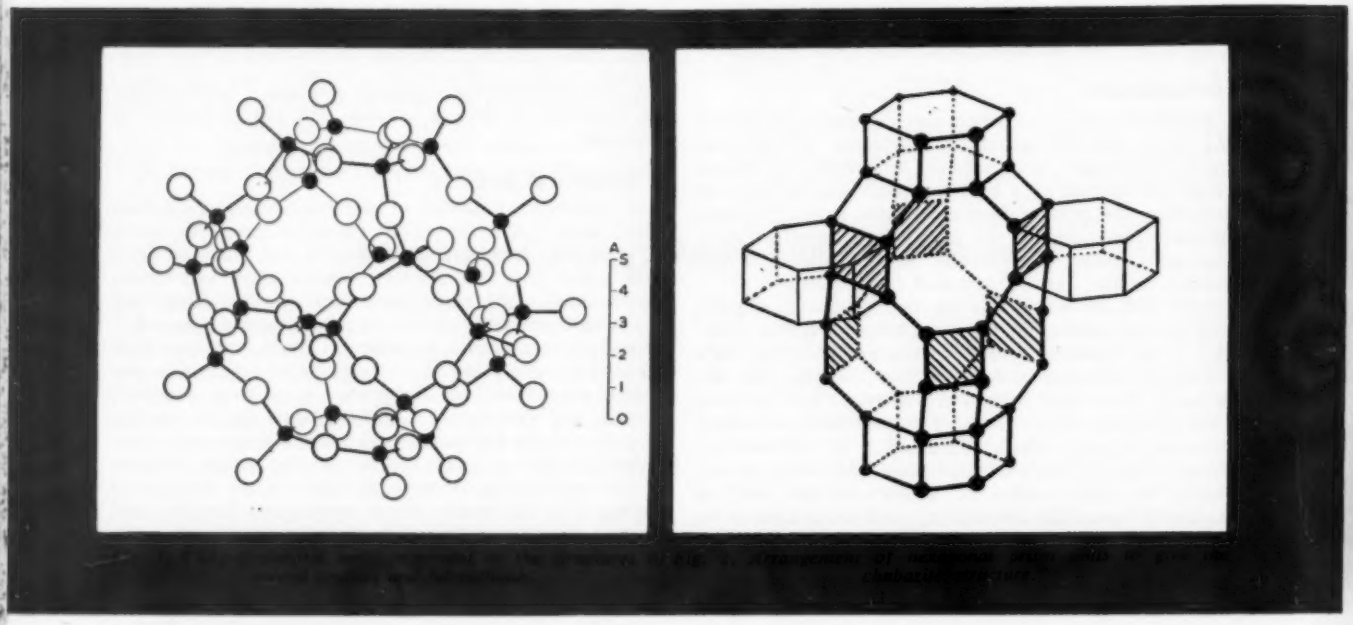
By stacking cubo-octahedra in tetrahedral co-ordination, as shown in Fig. 4,[28] one obtains the framework characteristic of faujasite, and of faujasite-type crystals such as Linde sieve X. Again very large additional cavities are produced by this mode of stacking, together with hexagonal prisms. The free diameters of the largest cages are ~12Å, and four 12-membered ring windows of free diameter 8 to 9Å lead into each of four other similar cavities. These cavities can hold about 32 water molecules.

3. Sorptive Capacities of Some Porous Crystals

Despite their open character, chabazite, Linde sieve A and faujasite, or faujasite-type Linde sieve X, when freed of their intracrystalline water, are remarkably stable to heating, and can stand temperatures up to 500°C almost indefinitely and even higher temperatures for considerable periods. When they or other suitable robust three-dimensional framework zeolites are dehydrated they develop great sorptive capacities for molecules small enough to pass through the windows referred to in the previous section. Table 1 compares the monolayer equivalent areas of some molecular sieve sorbents and of some active sorbents of a general-purpose type.

Alumino-silicate crystals which have been observed to act as sorbents by occlusion of gases include near-faujasites[20, 27] (Linde sieve X), Linde sieve A,[28] chabazite,[1, 29] gmelinite,[3] erionite,[30] levynite[6, 27] and mordenite.[3] Analcite, harmotome, phillipsite, synthetic zeolites of the harmotome family, zeolites of the natrolite family, stilbite and heulandite usually sorb only small polar molecules such as water or ammonia.[1, 31] Porous crystals containing Ga in place of Al and Ge in place of Si have also been synthesised.[14]

Other porous crystal sorbents have recently been developed from bentonites.[32, 33, 34, 35] This material is composed mainly of the layer-lattice clay, montmorillonite. Even when inter-lamellar water is removed the alumino-silicate lamellæ can be kept apart if the Na^+ or Ca^{++} ions are first exchanged for $CH_3NH_3^+$, $(CH_3)_2NH_2^+$, $(CH_3)_3NH^+$, $(CH_3)_4N^+$ and $(C_2H_5)_4N^+$. At the same time these ions are not large enough to occupy all the inter-lamellar space, so that the clays develop a high inter-lamellar surface, as indicated in Table 1. This surface is often accessible to permanent gases, inorganic vapours, aromatic hydrocarbons, *n*- and *iso*-paraffins, naphthenes and derivatives of these hydrocarbons. These sorbents can be very highly selective towards mixtures of molecules having different shapes. It is, however, possible by penetration of sorbates to separate the sheets further, and so quantitative molecular sieve separations characteristic



* By "free" is meant not occupied even by the peripheries of oxygen atoms of the framework.

† There is a slight waist around the middle of this cavity.

‡ Sepiolite and attapulgite have systems of parallel non-intersecting channels running parallel to the fibre axis.[26] These, however, are not generally accessible to sorbates, with the possible exception, and to a limited degree, of small polar molecules.[27, 28]

§ This has already been necessary to some extent. In previous communications[4, 43] three of these were first given and called Classes 1, 2 and 3. Subsequently, four classes were defined, and named Classes A, B, C and D.[43] B, C and D correspond respectively to the original Classes 1, 2 and 3. We now have Classes 1, 2, 3, 4 and 5, of which 3, 4, 5 correspond to 1, 2, 3 of reference 4; and 1, 3, 4 and 5 correspond to A, B, C and D of reference 43.

of rigid porous frameworks are not to be expected. Nevertheless, as noted, selectivity can be very great, and these "expanded clay" sorbents have also certain differences from rigid framework porous crystal sorbents which could be of value. Thus:

(i) they can be made much more organophilic so that intersheet water is only relatively weakly sorbed and is easily removed;

(ii) although less stable to heating than gas-sorbing zeolites, high purging temperatures are not necessary, and intercalated sorbates are normally readily removed. The "surfaces" developed by expanded bentonites are seen from Table 1 to compare with that of "Vycor" porous glass, or with such non-porous crystalline sorbents as attapulgite and sepiolite,‡ although they are smaller than are monolayer equivalent areas of gas-sorbing zeolites.

size is the least well characterised among the zeolites of Table 2. However, only partial sorption of 6-decyl-1,2,3,4 tetra-hydronaphthalene or of 2-butyl-1-hexylindan was observed,[40] suggesting a slow sorption of these species and that the cut-off is for about this molecular magnitude. Sieve 13X sorbed these molecules quantitatively, as well as 1,3,5-triethyl benzene which was not sorbed by sieve 10X.

It will be seen from the table that five main classes of molecular sieve crystal are defined. There are, however, definite shades of distinction within a given class. In Section 2 it was indicated that the free diameters of the windows leading into chabazite are ~3.9Å, while those leading into Linde sieve A are ~4.2Å. Each structure admits *n*-paraffins and excludes branched chain paraffins, but with finer distinctions in the yardstick molecules differences can be demonstrated. Such a difference can arise in rates of sorption. *n*-Paraffins diffuse into Ca-rich chabazite at a velocity which decreases with increasing

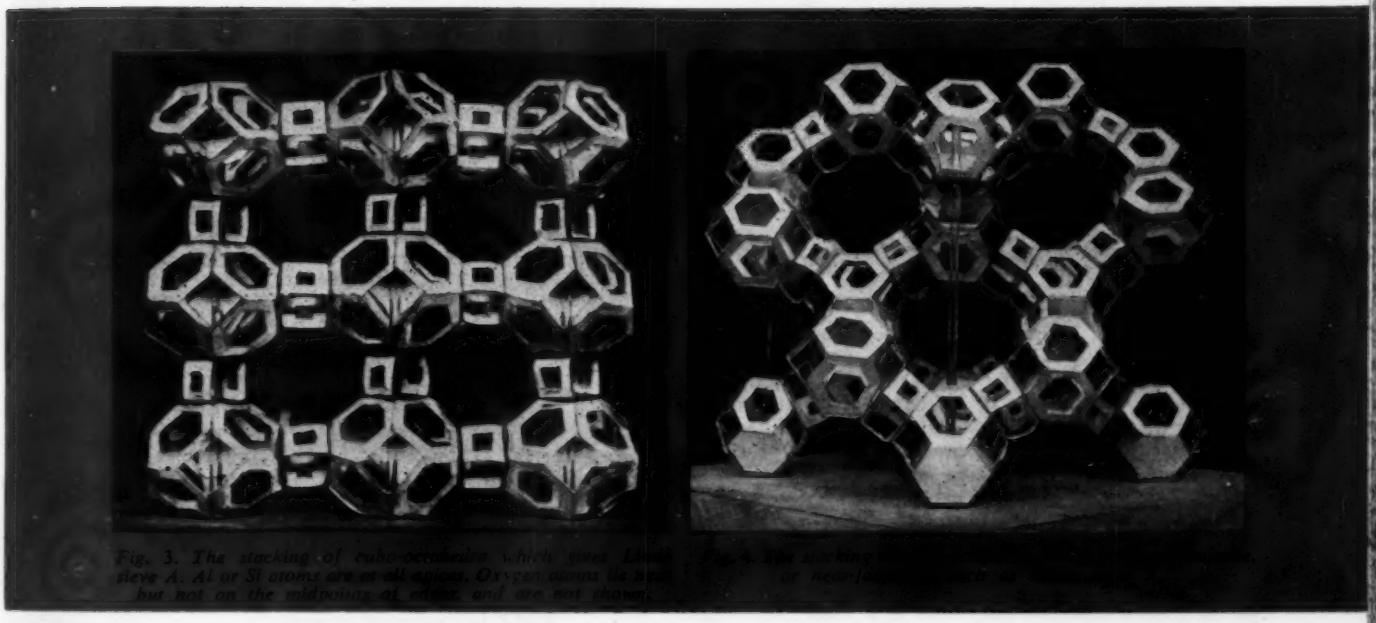


Fig. 3. The stacking of cuboctahedra which gives Linde sieve A. Al or Si atoms are at all apices. Oxygen atoms lie near but not on the midpoints of edges, and are not shown.

Fig. 4. The stacking [illegible] or near-faujasite [illegible]

4. Classes of Rigid Framework Crystal Sieves

The rigid, three-dimensional framework, porous crystal sorbents can be classified by their capacity to sorb, or their inability to sorb, a range of molecules of increasing molecular dimensions. For example, *n*-butane will penetrate into the lattice of dehydrated chabazite, or into that of Linde sieve 5A, but *iso*-butane having a branched chain will not. By means of such "yardstick" molecules, one may classify a number of zeolites as in Table 2. Thus all molecules in this table are sorbed by Linde sieve 13X (the Na-form of a synthetic faujasite-type zeolite) except *n*-perfluorotributylamine.[27, 30, 39, 40] We can predict from the crystal structure (see Section 2) that for a spherical molecule the limiting molecular dimension would be about 10Å, a little more than the free diameters of the windows leading to and from the largest cages in the structure. Although based on the same crystal lattice, Linde sieve 10X (the Ca-form of synthetic faujasite-type crystals) does not admit molecules as large as does sieve 13X, probably owing to the location of the Ca^{++} ions in the lattice. The position of the cut-off in sorption in relation to molecular chain length, and has become small for *n*-C_7H_{16}.[2] However, sieve 5A will sorb *n*-tetradecane quite freely.[41] Other differences are shown in the behaviour of these sorbents towards boroethane[41a] and Freon-type molecules (*q.v.*). Apart from these finer distinctions, it is quite possible that new major classes of crystal sieve will be discovered in the future, with further need for renumbering the main categories of sieve.§

The question of molecular sieve limits can be usefully approached by considering the critical dimensions of sorbate molecules which will allow them to pass through the appropriate windows (cf. Section 2), giving access to the intracrystalline cavities of the molecular sieve sorbent. Thus, in a spherical molecule such as argon, the critical molecular dimension is its diameter. Since the windows leading into possibly accessible cavities are 6-, 8- or 12-membered rings, fairly regular in shape, they may to a first approximation be regarded as approximately circular. Then the diameter of the spherical sorbate molecule must not be appreciably greater than the free diameter of the window. If the windows are elliptical in shape, as appears

to be the case for erionite,[22] the diameter of the spherical molecule must not be appreciably greater than the minor axis of the ellipse. The atoms composing molecule and ring are to some extent soft, and so molecules a little larger than the free diameter of the window can pass through it, although with an energy of activation which rises rapidly as the molecular diameter increases.[44, 45] The rare gas atoms, to which we may also add methane,* have critical diameters in Å as follows:

He	~2.0	Kr	3.9_4
Ne	3.2_0	Xe	4.3_7
A	3.8_3	CH_4	4.0 (4.4_4)

For very symmetrical tetrahedral molecules such as CF_4 or CCl_4, the critical dimension in a non-rotating state will tend to be the diameter of the circle circumscribing the triangular base of the molecule. Using bond distances and van der Waals' atomic radii as given by Pauling,[46] we obtain the values in Å:

CF_4	5.3_3 (5.4_4)	CI_4	8.2_2 (8.5_0)
CCl_4	6.8_8 (7.1_2)	$C(CH_3)_4$	6.8_8 (7.0_8)
CBr_4	7.4_6 (7.7_2)	SF_6	6.0_6 (6.0_6)

If the molecules are rotating freely, then the critical dimension is the diameter of the circumscribing sphere, which is given in brackets. Corresponding figures are also given above for the octahedral molecule SF_6.

In the case of diatomic or di-radical molecules, the critical molecular dimension will normally tend to be the diameter of the circle circumscribing the molecule normal to its length. Several examples are:

H_2	2.4 (3.1_4)	C_2H_6	4.4_4 (4.6_0)
O_2	2.8 (3.9_0)	C_2F_6	5.3_3 (5.1_1)
N_2	3.0 (4.0_8)	C_2Cl_6	6.8_8 (6.2_3)

(The figures in brackets denote the lengths of the molecules.)

When we come to *n*-paraffin molecules the critical dimension is again the diameter of the largest circle needed to circumscribe the molecule in a plane normal to its length. This dimension of ~4.9Å is the same for all *n*-paraffins in a stretched-out configuration which all may assume; and hence there is a simple explanation of the experimental observation that if propane or *n*-butane penetrates the crystals, so do other longer chain *n*-paraffins.

If a substituent group is attached to a secondary carbon atom along a *n*-paraffin chain, it is again the diameter of the greatest circumscribing circle in a plane normal to the length which should be the important dimension. For elliptical windows this dimension must not exceed by much the major axis of the ellipse, nor must the third dimension normal both to length and to maximum breadth of the molecule exceed the minor axis of the ellipse. With disc-shaped molecules such as benzene or pyridine the critical dimension is the diameter of the circle circumscribing the disc, with the thickness of the disc normal to its plane as a subsidiary critical dimension in the case of elliptical windows. In the case of unsymmetrical molecules such as $CHFCl_2$ or CHF_2Cl the diameter of the smallest circle that can be drawn to circumscribe the molecule is a critical dimension.[47] The Freon-type molecules are of interest in that they serve to differentiate between Linde sieve 5A and chabazite, both classed as type 3. Thus, CF_3Cl and CF_2Cl_2 are sorbed by sieve 5A, though not by chabazite. CHF_2 and CHF_2Cl, on the other hand, are sorbed by both chabazite and sieve 5A. With more complex molecules still, such as decahydrochrysene, other

* The van der Waals' radius of CH_3 is taken to be the same as that of $-CH_3$, which is 2.0Å as given by Pauling.[46] This approximate view regards the CH_4 and $-CH_3$ as spherical, which is an obvious but not serious approximation. Considering CH_4 as a tetrahedral molecule, a critical dimension of 4.4₄Å is obtained (cf. CF_4, etc.).

TABLE 1. Monolayer Equivalents of Porous Crystals* and of Other Typical Sorbents [26]

Porous Crystal	Equivalent Area (sq. m./g.)	Active Sorbent	Area (sq. m./g.)
Near-faujasite, Na-form (Linde sieve 13X)	1030	"Carbolac" carbon	1060
Near-faujasite, Ca-form (Linde sieve 10X)	1030	"Carbolac" carbon, compressed to porosity 0.53 c.c.³c.c.³	890
Linde sieve 4A (Na-A)	~800	Carbon wear dust	770
		Silica gel	610
Linde sieve 5A (Ca-A)	750-800	Silica gel	580
Chabazite, Ca-rich	750	Activated alumina†	230-380
Mordenite	440	Sepiolite	310(max.)
CH_3NH_3-bentonite	160(135)‡	Attapulgite	260(max.)
$(CH_3)_3NH_2$-bentonite	150(110)‡	"Vycor" porous glass	140
$(CH_3)_2NH$-bentonite	130(95)‡		
$(CH_3)_4N$-bentonite	140(110)‡		

* The areas are recalculated if necessary to give their values per g. of the anhydrous sorbent. The original references are summarised in reference 26.

† An undetermined amount of residual water is present.

‡ Figures in brackets are estimates of interlamellar areas available for sorption. Figures not in brackets are sums of interlamellar and external areas of crystallites. The bentonite used contained some impurity (*e.g.*, quartz).

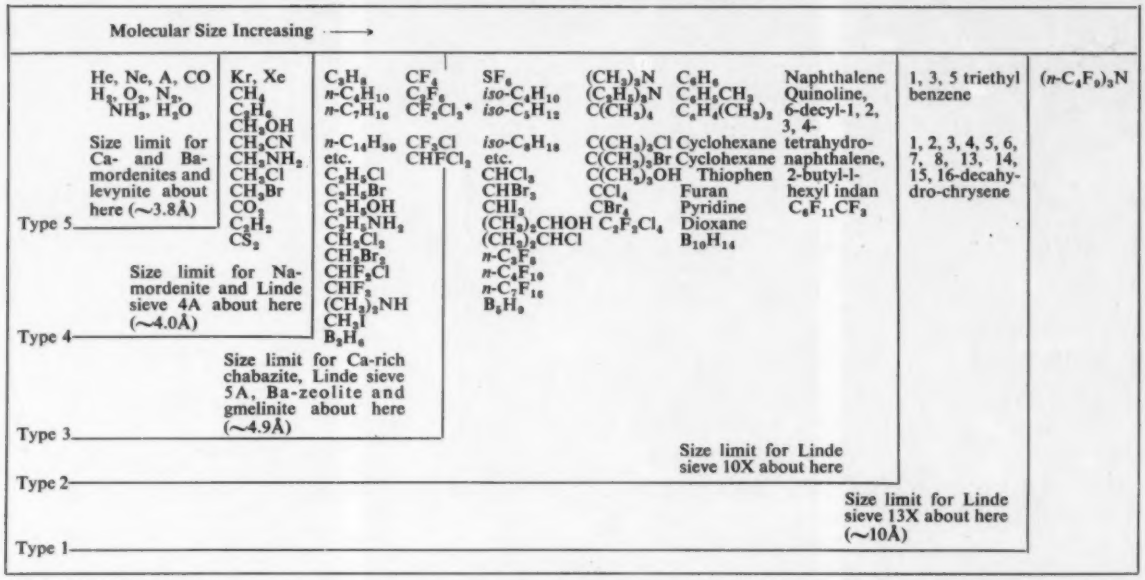
TABLE 4.—Approximate Relative Amounts of Three Portions, Obtained by Fractionation Separately, of the Mono-, Di- and Tri-nuclear Aromatics C_{18} to C_{28}[40]

Original Material	Fractionated Portions		
	Not sorbed by 13X	Sorbed by 13X and not by 10X	Sorbed by 10X
	% by Volume		
Mono-nuclear aromatics	30	58	12
Di-nuclear aromatics	60	33	7
Tri-nuclear aromatics	58	26	16

TABLE 4a—Analyses of Kerosenes [40b]

% by Volume	Kerosene sample					Test Blend of *n*-paraffins	
	1	2	3	4	5	Actual composition	Composition by GLC
Individual *n*-paraffins by subtractor method with GLC							
C_7	Trace	—	—	Trace	—	—	—
C_8	1.0	0.6	0.2	0.1	0.8	—	—
C_9	4.9	3.6	0.6	0.9	1.8	3.1	3.4
C_{10}	5.3	5.2	1.8	2.3	1.7	7.7	8.3
C_{11}	4.8	8.4	6.5	2.4	1.5	22.6	22.5
C_{12}	3.9	6.2	5.5	2.2	1.1	29.8	29.7
C_{13}	1.9	2.3	4.8	1.9	0.7	22.2	22.5
C_{14}	0.9	0.5	4.0	1.3	0.4	14.6	13.6
C_{15}	0.3	0.2	1.9	0.6	—	—	—
C_{16}	—	—	0.7	0.3	—	—	—
Total *n*-paraffin by subtractor method with GLC	23	31	26	12	8		
Total *n*-paraffin by sieve 5A (liquid phase separation)	22	27	26	11	9		

TABLE 2. Classification of some Molecular Sieves



* Freon-type molecules provide interesting border-line cases and can differentiate between certain of the zeolites grouped as Type 3. Simple ketones and esters are also border-line cases.

TABLE 3. Typical Separations of Hydrocarbon Mixtures

Molecular Sieve	Mixture	Component Sorbed	Remarks on Separation
Linde sieve [40] 10X (Type 4)	Dodecahydrochrysene + *n*-decyl benzene	*n*-decyl benzene	Pure dodecahydrochrysene from non-sorbed eluant; 97% *n*-decyl benzene recovered from zeolite by steaming
Linde sieve [41, 48] 5A (Type 3)	Benzene + *n*-tetra-decane	*n*-tetradecane	99.9% benzene recovered from mixture
	Methyl cyclohexane + *n*-heptane	*n*-heptane	Pure methyl cyclohexane recovered from mixture
	3-methyl heptane and *n*-heptane	*n*-heptane	q*
	Toluene and *n*-heptane	*n*-heptane	q
	Toluene and *n*-octane	*n*-octane	q
	2, 2, 4-trimethyl pentane and *n*-decane	*n*-decane	q
Chabazite[4] (Ca-rich) (Type 3)	Isobutane and propane	propane	q
	Isobutane and *n*-butane	*n*-butane	q
	Isopentane and *n*-butane	*n*-pentane	q
	Isopentane and *n*-pentane	*n*-pentane	q
	Isopentane, propane and *n*-butane	propane and *n*-butane	q
	Toluene, cyclohexane and *n*-butane	*n*-butane	q
	Iso-octane and *n*-heptane	*n*-heptane	q
	Toluene and *n*-heptane	*n*-heptane	q
Ba-zeolite[7] (Type 3)	Isobutane and *n*-butane	*n*-butane	q
	Isopentane and *n*-butane	*n*-butane	q
	Benzene and *n*-butane	*n*-butane	q
	Isobutane and propane	propane	q
	Isobutane and ethane	ethane	q

* q denotes quantitative removal of sorbed component.

critical dimensions can be visualised, but the situation becomes more complicated.

For the simpler species the critical dimensions are useful in predicting whether sorption will occur. Thus in chabazite or Linde sieve 5A, since the yardstick molecule, propane, penetrates into the crystals, so will other species of similar shape and size, such as ethyl chloride, ethyl bromide, methylene dichloride and methylene dibromide, although at somewhat different velocities *inter se*. Similarly, since *iso*-butane is not sorbed by the above two zeolites, neither should be chloroform nor bromoform which have similar shape and size to *iso*-butane. These predictions and others of similar character have been fully verified by experiment. That molecular shape and not molecular volume can be all-important is indicated by, for example, the observation that while *iso*-butane does not penetrate chabazite, *n*-heptane, which has a *greater* molecular volume but a *smaller* critical dimension, is sorbed.

5. Separations of Hydrocarbons

The number of separations which can be effected using molecular sieve sorbents is very large. Uses in the field of hydrocarbon technology will first be illustrated. Various binary or more complex mixtures have been examined in all of which quantitative separations were effected in a single stage (Table 3). The separations involving sieves 10X and 5A were carried out by passing a mixture through a column of the zeolite near room temperature; in those involving chabazite and the barium zeolite, static liquid or vapour mixtures were contacted with the zeolite in the range 150° to 220°C, except for that involving ethane, which was carried out at room temperature. Unlike gas-liquid partition chromatography, the molecular sieve method is well suited to handling bulk samples and for recovering or purifying substantial quantities of materials. Type 3 molecular sieves are seen, from the data presented in the table, to be excellent for separating *n*-paraffins from

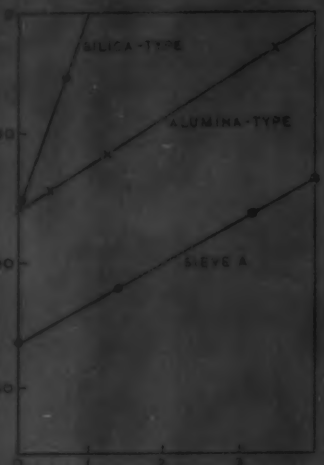


FIG 5

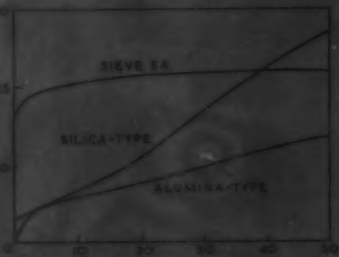


FIG 6

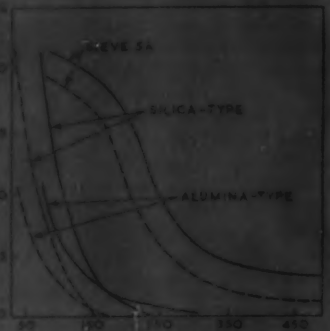


FIG 7

FIG 8

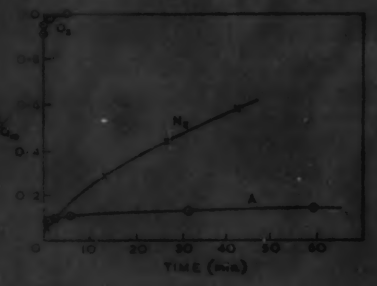


FIG 9

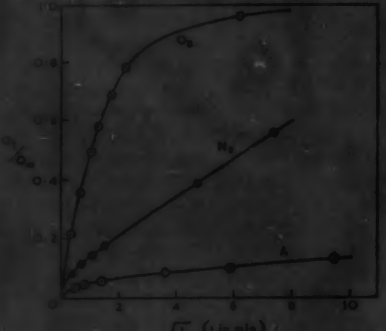


FIG 10

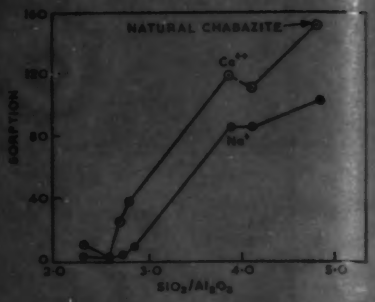


FIG 11

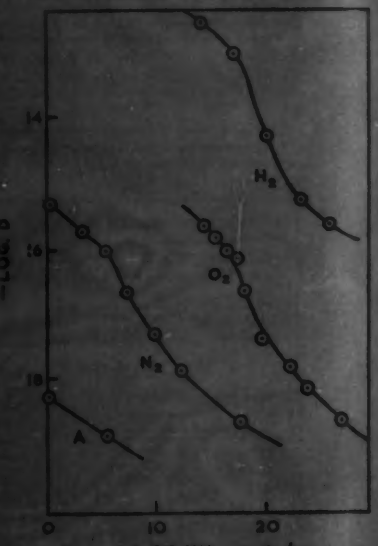


FIG 12

Fig. 5. Dew points obtainable in an air stream, initially at 10% R.H., at 1 atm. and 100°F under dynamic drying conditions with silica-type, alumina-type and molecular sieve desiccants. The performances are shown as a function of % residual water in the desiccants.[10]

Fig. 6. Water vapour sorption at 25°C on molecular sieve, silica-type and alumina-type desiccants.[10]

Fig. 7. Water vapour sorption isobars at 10 mm partial pressure on molecular sieve, silica-type and alumina-type desiccants. The dotted lines show the effect of 2% residual water on the weight % additionally sorbed.[10]

Fig. 8. Occlusion of A, O_2 and N_2 by a faujasite-type sorbent (O_2, A: ●, O_2, X, N_2). The strong preference for nitrogen is shown at 273° and 194.5°K. At 90°K the crystals become saturated with respect to all the gases so that selectivity is not shown merely by inspection of isotherms.

Fig. 9. Widely divergent sorption rates in dehydrated levynite at −184°C, due to the molecular sieve activity of the zeolite.[9] *Q_t denotes cc sorbed at stp/g at time t. Q_∞ denotes amount sorbed at equilibrium, in cc at stp/g. For O_2, Q_∞ = 10.02; for N_2, 9.77; and for A, 10.13.*

Fig. 10. Relative sorption rates of N_2, A and O_2 in Ca-mordenite at −78°C.[11]

Fig. 11. Influence of the replacements $(\frac{1}{2}Ca)Al \rightleftharpoons Si$ and $NaAl \rightleftharpoons Si$ on the sorption of oxygen by chabazite-type sorbents at −183°C and 20 cm pressure.[12] *The ordinate gives the sorption in cc at stp for a fixed number of unit cells, viz. the number in 1 g. of the hydrated K-form in which $SiO_2 : Al_2O_3 = 4.15:1$.*

Fig. 12. The change in diffusion coefficient D, ($cm^2\ sec^{-1}$) in mordenite at −183°C as a function of the amount of modifier (NEJ) present.

TABLE 5. (a) Separations of Hydrocarbon Mixtures using 2.7 g. of NMe_4+—bentonite in a 50 cm. Column of 3.5 mm. Diameter[51]

Mixture		Mol. Fract. of *A*	Volume of Mixture Separated (cm.³liq)	Temperature of Column (°C)	Component Selectivity Retained by Sorbent
A	*B*				
Benzene	Cyclohexane	0.705	0.340	77	Benzene
Toluene	Cyclohexane	0.540	0.345	77	Toluene
Benzene	Toluene	~0.4	0.340	77	
n-heptane	*Iso*-octane	~0.55	0.293	20 and 130	*n*-heptane
n-heptane	Cyclohexane	0.555	0.360	20, 77 and 130	*n*-heptane
n-hexane	Cyclohexane	0.22	0.293	22, 77 and 130	*n*-hexane
Benzene	*n*-heptane	0.645	0.362	77	Benzene

TABLE 5. (b) Separations of Hydrocarbon Mixtures using ~2.5 g. of $NMeH_3$+—bentonite in a 50 cm. Column of 3.5 mm. Diameter

Benzene	Cyclohexane	0.705	0.157	77	Benzene
Benzene	*Iso*-octane	0.63	0.139	77	Benzene
n-heptane	*Iso*-octane	~0.5	0.139	77	*n*-heptane

iso-paraffins, aromatics and naphthenes. From the less complete information regarding sieve 10X in Tables 2 and 3, this sorbent would be expected to separate many monocyclic aromatics and naphthenes and less highly branched *iso*-paraffins and *n*-paraffins from many di- and tri-cyclic aromatics and naphthenic species. Further evidence on this type of application is given below.

Analytical procedures of interest have been developed which are the logical outcome of experiments such as those involved in obtaining the data presented in Tables 2 and 3. One of these[40] employs sieves 10X and 13X for fractionating hydrocarbon mixtures, composed of petroleum fractions rich in mono-, di- and tri-nuclear aromatics in the C_{18} to C_{25} range. The mixtures were introduced into columns of the molecular sieves, the non-sorbed portions were eluted with *iso*-octane and finally the sorbed constituents were removed with superheated steam or, preferably, with alcohol at its boiling point. The overall results of the experiments are summarised in Table 4. The further fractionation of higher boiling petroleum fractions using sieves 10X and 13X should prove a useful method for investigating the composition of such fractions. Normal sorbents, solvent extraction or azeotropic distillation tend to separate hydrocarbons according to type, whereas molecular sieve adsorbents separate according to the shape and size of the molecules being fractionated. Combinations of these methods can therefore be particularly useful.

Schwartz and Brasseux[48] used a molecular sieve method for determining the *n*-paraffin content of olefin-free raffinates. The petroleum sample was first distilled to yield fractions containing only one of the *n*-paraffins heptane, octane, nonane and decane. These distillates were then fractionated further by passing them through a column of sieve 5A. The *n*-paraffin was completely removed in this operation, while *iso*-paraffins, naphthenes and aromatics passed through the column unsorbed. The refractive indices of the original raffinate, the non-sorbed eluate, and the pure *n*-paraffin were then used to find the *n*-paraffin content of the raffinate. An average error of less than 2% of the *n*-paraffin content was obtained. The method requires only simple apparatus, in contrast to infra-red, mass-spectrometric and gas-chromatographic procedures, which involve also careful calibration.

The use of sieve 5A permits the determination of both *n*-paraffins and *n*-olefins in petroleum distillates.[49] Distillates boiling in the range 60°F to 400°F were studied. A weight w_1 of zeolite was mixed with the distillate and the whole reweighed (w_2). Non-sorbed hydrocarbons were then distilled off at 100°C and zeolite plus sorbed *n*-paraffins and olefins were reweighed (w_3). The percentage of *n*-paraffins and olefins is then $\frac{w_3-w_1}{w_2-w_1} \times 100$. The *n*-paraffins were then determined by analysing in the same way the acid-treated raffinate of the distillate, and finally the *n*-olefin content was found as the difference between the first and second determinations. An accuracy of ±0.5% was reported and the whole determination was rapid and used only simple equipment.

Molecular sieve columns can be effectively combined with normal gas-chromatography columns. The method was first used successfully for determining C_3 to C_{11} *n*-paraffins in the gasoline range,[49a] and then further developed for quantitative analysis of *n*-paraffins in kerosenes and gas oils.[49b] A chromatogram was first obtained for a petrol fraction. Then a second chromatogram was obtained after first passing the petrol fraction through a short column of sieve 5A and finally through the chromatographic column. The molecular sieve acts as a subtractor of all *n*-paraffins, the peaks for which are now missing. Subtracting the area of the second chromatogram from that of the first gave a measure of the total *n*-paraffin content. The amount of each individual *n*-paraffin was similarly obtained from the difference in peak area at the respective *n*-paraffin elution times of the two chromatograms.[49b] The pre-column of sieve 5A was kept at 150°C and coated with 1.6% squalane to prevent tailing effects. The gas-liquid chromatography column coated with 26% of silicone grease was operated at 164°C. Results are summarised in Table 4a. The quantitative accuracy of the GLC (gas-liquid chromatography) is shown in the analysis of the test blend of *n*-paraffins in the last two columns. In the first six columns are given the individual *n*-paraffin contents of five kerosenes, the total *n*-paraffin contents, and this content determined by a procedure, using sieve 5A, analogous to that of Schwartz and Brasseux.[48] Whitham[49b] has also reported promising results for waxes containing *n*-paraffins up to C_{40}, using nitrogen as carrier, running the subtractor column of sieve 5A at 320°C without squalane, and the main GLC column at 270° to 300°C. This subtractor method has a range of possible applications for complex mixtures other than hydrocarbons.

The foregoing analytical uses indicate one type of application to petroleum technology. In addition, however, a whole range of uses is possible in the purification of aromatic, naphthenic or *iso*-paraffinic hydrocarbon chemicals. As an example, commercial isopentane was stripped of *n*-paraffin impurities by passing the liquid through a column of sieve 5A.[41] The impure isopentane contained about 9% of *n*-paraffins, but after treatment no *n*-paraffins could be detected by infra-red study of the non-sorbed fraction, up to the point of break-through of *n*-paraffins. This occurred at an *n*-paraffin loading of 12% by weight occluded within the sorbent. The freezing point indicated that other *iso*-paraffins were also present. Purification of other hydrocarbons (*n*-dodecane and isosafrole) has also been reported, using sieve 5A.[41]

TABLE 6

Drying Agent	Conditions	Time for clouding to appear (hours)
(1) $Mg(ClO_4)_2$ followed by phosphoric oxide	Room temperature. Absorption tubes 2-5 cm.×120 cm. long	1
(2) As in (1), followed by passage through a sodium filter*	As in (1), but sodium filter at 100°	4-5
(3) Linde molecular sieves 4A or 5A	Room temperature. Single absorption tube 2.5×120 cm.	Surface bright indefinitely†

* This is the filter used in the initial filtration of liquid Na. The argon passes through the sintered glass plate which contains some oxides of sodium.

† The longest duration of any one experiment was about 8 hours, but a single absorption tube was used intermittently for 80 hours without regeneration.

TABLE 7
Enrichment Factors in Sorption

Mixture $A + B$	Range in η at −183°C (sorption)	η'(liquid-vapour equilibrium)
$O_2 + Ne$	~1000 (mordenite)	—
$H_2 + Ne$	55-10 (mordenite)	0.2 (−250°C)
$O_2 + A$	7.5-5 (chabazite)	1.75
$N_2 + A$	11-1.2$_5$ (chabazite)	0.37

TABLE 8. **Relative Rates of Intracrystalline Flow in some Zeolites**

Crystal	Temperature, °C	Sequence of Relative Rates
Li-mordenite	−185	H_2, O_2>N_2>Ne>A
	− 78	O_2, N_2>A>Kr
	20	O_2, N_2>A>Kr
Na-mordenite (synthetic)	−185	O_2, H_2>Ne>A
	− 78	A>Kr
	20	A>Kr
K-mordenite	−185	H_2>O_2>N_2>A
	− 78	H_2>O_2>N_2>A>Kr
	20	O_2, N_2>A>Kr
NH_4-mordenite	−185	H_2, O_2>N_2>A
	− 78	H_2>O_2, N_2>A>Kr
	20	O_2>N_2, A>Kr
Ca-mordenite	−185	He>H_2>Ne>O_2>N_2, A
	− 78	O_2>N_2>A
	20	N_2>A>Kr
Ba-mordenite	−185	He>H_2, O_2>Ne>N_2>A
	− 78	O_2>N_2>A
	20	N_2>A>Kr
Levynite	−185	H_2, O_2>Ne>N_2>A
	− 78	N_2>A>Kr
	20	A>Kr

TABLE 9. **Relative Rates of Intra-crystalline Flow of a Given Gas in a Series of Crystals**

Gas	Temperature (°C)	Relative Rate Sequence for Various Crystals*
Kr	− 78	NH_4>Li>Na>K
	20	NH_4>Li>Na>Ba>K>Lev>Ca
A	− 78	Li>NH_4>Na>Ba>Lev>Ca
	20	Li>NH_4, Na>Ba>Lev>Ca
Ne	−185	Li>Ba>K>Lev>Ca
N_2	−185	Li>NH_4>Ba>Ca, K
	− 78	NH_4, Ba>Lev>Ca
	20	NH_4, Ba>Ca
O_2	−185	NH_4, Li, Ba>Lev>Ca>K
	− 78	Li>Ba>NH_4>Ca>K
H_2	−185	Na, Li>Ba>Lev>Ca>NH_4>K
	− 78	Li>NH_4>K

* In this column, Lev = levynite, Li = Li-mordenite, NH_4 = NH_4-mordenite, etc.

Before leaving the important field of hydrocarbon separation, one may comment upon the possible use of the porous, expanded bentonite sorbents, referred to in Section 3. Tetramethyl ammonium bentonite shows a notable preference for some aromatic hydrocarbons as compared with *n*- or *iso*-paraffins and naphthenes. There is also in a number of porous bentonites selectivity of *n*- as compared with *iso*-paraffins. By adsorption chromatography at high loadings good separations were obtained in the examples of Table 5.[35] These crystals do not show molecular sieve action as complete as many of those found with rigid framework zeolites. Nevertheless, the expanded bentonite sorbents are more readily activated and also freed of sorbed species and the affinities between sorbate and sorbent do depend in part upon molecular shape and size. In order to insert more bulky molecules between the alumino-silicate sheets, these sheets must be still further separated by an amount depending upon the dimensions of the sorbate. Sheet separation is an endothermal process which reduces the affinity between sorbate and sorbent according to the extent of the additional expansion. The special affinity shown between simple aromatic molecules and tetramethyl ammonium bentonite on the other hand appears to arise in part from interaction between π-electrons and inter-lamellar cations, the aromatic rings being oriented vertically between the alumino-silicate layers.[34]

6. Molecular Sieves as Desiccants

A very important range of applications, both on industrial and on laboratory scales, involves the use of molecular sieve sorbents as desiccants. Drying agents which act by adsorption include silica gel and activated alumina; in addition, "chemical" desiccants may be employed such as magnesium perchlorate and calcium sulphate. Much attention has been paid to the extremely good properties of molecular sieve zeolites as drying agents, and, in general, the following aspects appear to have been established.[50]

(i) Gases may consistently and continuously be dried to give dewpoints below −100°F under large-scale production conditions. The performance of a Linde sieve type A as compared with a silica gel and an activated alumina is illustrated in Fig. 5. Similar performances could be anticipated with other zeolites such as chabazites, gmelinites or mordenites.

(ii) Molecular sieve crystals can readily and completely dry gases which already have a low relative humidity. Moreover, drying operations are successful even when the gases being dried are at elevated temperatures of 200°F or above.

(iii) The retentivity of zeolites to water is such that moisture can be removed thoroughly when the gas stream has a rather high velocity.

(iv) The sieve crystals can often be chosen so that other components of the gas stream are not sorbed, and therefore there is no likelihood of altering the composition of the stream. On the other hand, they can also be chosen so as to remove other impurities, besides water, selectively and completely.

The advantage which a molecular sieve zeolite may possess over silica and activated alumina can be demonstrated by comparing the isotherms and isobars for the three types of sorbent.[50] This is done in Figs. 6 and 7. From the first of these figures it is evident that Linde sieve type A can at low relative humidity hold nearly five times as much moisture as can a typical silica gel or activated alumina. Similarly, Fig. 7 demonstrates the greatly superior moisture retentivity of sieve 5A at higher temperatures, for example, at 150°F. As an illustration of what may be done in complete drying, one may refer to

the effectiveness of molecular sieves in maintaining clean surfaces on liquid sodium and bismuth. Liquid metals are used as coolants and solvents in nuclear reactors. Their surfaces are prone to tarnish in the presence even of very small traces of moisture. Argon, dried by various means, was passed over a bright liquid metal surface at a constant rate (0.5 l./min.) and the time required to produce the first observable tarnishing was noted. The results are summarised in Table 6.[51] Liquid bismuth provided a still more exacting test. At 300-500°C it tarnished almost at once in the presence of argon dried by procedures (1) or (2) of the table. However, if argon was passed through the molecular sieve and then through manganous oxide to remove traces of oxygen, a bright liquid bismuth surface was maintained for some hours.

The process of water vapour sorption is strongly exothermal in various desiccants, and molecular sieve sorbents are no exception in this respect. Indeed, polar molecules in general are occluded by these heteroionic sorbents very energetically, so that a considerable temperature rise can occur. Temperature rises in the less energetically sorbing desiccants can impair their performance by raising their temperature to a point where desorption is considerable (cf. Fig. 7). Under such circumstances, there has to be cooling of the desiccant. Zeolite desiccants, however, because of their high water retentivity, can suffer substantial temperature increases without significant loss in break-through capacity or in efficiency. Consequently, gas streams may be dried under semi-adiabatic conditions.[50]

It is often the case that more than one impurity, including water, has to be removed from a gas stream. At 25°C and 5 mm pressure the relative amounts sorbed by Linde sieve 5A and a silica gel in a number of cases were[50]:

Gas	*Capacity Ratio Sieve 5A/Silica Gel*
Carbon dioxide	5
Ammonia	2
Acetylene	8
Propylene	20
Ethane	5
Carbon monoxide	3 (−78°C)
Ethylene	3
Propane	8
Butene-1	4

The sorption affinity is substantially greater in the zeolite, which can therefore act more satisfactorily in co-adsorption than the gel. In general, the water adsorption front moves most slowly through the column and displaces other adsorbed species in front of it. The technical arrangements in a co-adsorption unit are guided by this fact. An industrial application is found in the purification of annealing gas, from which water and carbon dioxide have to be removed. Some details are given below[50]:

Molecular Sieve Requirements	*570 lb. per bed per hour of adsorption*	
Inlet conditions	Generator capacity:	2000 cu. ft per hr
	Carbon dioxide concentration:	12% by volume
	Water concentration:	+40°F dewpoint
Outlet conditions	Carbon dioxide concentration:	<10 ppm by volume
	Water concentration:	<−100°F dewpoint
Cycle time for each bed	½ hr—adsorption ½ hr—regeneration ½ hr—cooling	
Bed regeneration temperature	600°F.	

Another co-adsorption problem involves removal of water and ammonia from nitrogen-hydrogen mixtures ("dissociated ammonia") used as annealing gas. In this case also, purification to the required degree was successfully achieved.[50]

An important field for the use of molecular sieve desiccants appears likely to be the refrigeration industry.[50] Although Freons do not mix with water, they may entrain small amounts of moisture. This, by freezing out, can cause blockages in expansion valves, by reaction with refrigerants it may produce traces of corrosive, or it may promote electrolytic corrosion. The water content should not rise above 10 to 15 ppm, a desideratum that is readily achieved using zeolites. Some of these would also be expected to remove traces of acids, as has already been demonstrated using Linde sieve 5A.[50]

The foregoing comments have been concerned with dynamic drying operations. Zeolites also possess notable powers of intensive drying under static conditions. They will, for example, remove water from mixtures in which the other molecules are too large to penetrate the sorbent. There is thus the very favourable condition that no other chemical species are competing for the sorbent with the water, a condition which can apply whether the materials being dried are polar or non-polar. Thus it was demonstrated in 1945[4] that, by a total molecular sieve action, chabazite could dry ketones, ethers, dioxane, esters or secondary and tertiary alcohols; that Na-mordenite dries such species and also ethanol; and that Ca- and Ba-mordenites dry such species and also methanol and ethanol. Using Linde sieve A[50] ethanol containing 0.5% by weight of water has been dried to a moisture content of less than 10 ppm by a single passage through a bed of sorbent, while intensive drying of cyclic and aromatic hydrocarbons, pyridine, alcohols, ethers, amides, amines and alkyl halides has been demonstrated. Insulating oil can be dried without any parallel sorption of anti-oxidant such as *t*-butyl-*p*-cresol.

The usual method of reactivating water-saturated beds of molecular sieve zeolites is by heating in a stream of air or nitrogen. Local high concentrations of water vapour or liquid should be avoided especially at elevated temperatures, because all zeolites are subject in some measure to "weathering" reactions which may deteriorate them. This situation can be minimised by appropriate handling, especially for pelletised sieve sorbents, since then there is little resistance to air flow and the purge gas therefore carries away the evolved water without danger of its local accumulation in the sorbent. Under such circumstances a very large number of sorption and regeneration cycles is possible, which in the case of Linde sieve A has been given as 5000 for about 30% loss of the original sorptive capacity.[52] Zeolites differ *inter se* in their stability to attack by water, and for a given zeolite stability can also vary from one ion-exchanged form to another as well as with the treatment to which the sorbent is subjected.

7. Gas Separations

At suitably low temperatures incondensible gases may be sorbed by certain zeolites in large amounts.[1, 3, 27, 28] Such gases are, moreover, subject to molecular sieve actions exercised by crystals having "windows" of appropriate dimensions leading into the intracrystalline cavities of the sorbent. It is of interest to record some of the observations which have been made in this field.

Porous crystals may act as selective sorbents in the following three ways:

(i) In absence of any molecular sieve action, but as a result of different affinities of sorbable gases, vapours or liquids at equilibrium.

TABLE 10. Behaviour of Gas Mixtures ($A + B$) with Mordenite at −185°C

Sorption Properties of A and B in Mixture	Expected Preferential Sorption	Corresponding Mixture passed through Mordenite	Sorption Observed	Other Comparable Mixtures
Diffusion of $A>B$ Sorption of $A>B$	A removed	$N_2 + A$	N_2 removed	
Diffusion of $A>B$ Sorption of $A\sim B$	A removed	$O_2 + A$	O_2 removed	
Diffusion of $A>B$ Sorption of $A<B$	A or B could be removed	$A + Kr$	Separation not satisfactory	(*a*) $C_2H_6 + C_3H_8$ (in chabazite[4]). Good separation. (*b*) $O_2 + N_2$ (in Linde sieve 4A).
Diffusion of $A>B$ Sorption of $A\ll B$	B probably removed	$H_2 + A$ $H_2 + N_2$ $Ne + A$	A preferentially removed N_2 " " A " "	$H_2 + CO$

(ii) By partial molecular sieve action. In this case all the molecules in the mixture may penetrate the crystal, but owing to differences in molecular shape, size and affinity there are distinct differences in sorption velocity. These differences may be used to effect separations if the time of contact of the mixture and the crystals is suitably adjusted.

(iii) By total molecular sieve action, in which molecules $A, B, \ldots$, are copiously occluded, while molecules $X, Y, \ldots$, having the wrong shape and size, are completely unable to penetrate the crystal.

We may consider these possibilities in relation to zeolitic sorbents, in order.

(a) Equilibrium selectivity. Sorbents may differ substantially in their power to sorb a given molecule under comparable conditions of temperature and pressure. We may think of three categories of sorbent:

heteroionic sorbents, e.g. zeolites;
anionic sorbents, e.g. silica gel;
covalent sorbents, e.g. outgassed activated carbons.

Heteroionic sorbents are characterised by having both cations and centres of negative charge exposed to the sorbate molecules. Anionic sorbents are characterised by having primarily or wholly anionic oxygen atoms presented directly to the sorbed molecules; while covalent sorbents possess no marked alterations of polarity and present non-ionic surfaces to the sorbate. To some extent this classification may be an idealisation. For example, activated carbons when outgassed normally retain some chemisorbed oxygen. It is, however, useful and offers an explanation of some observed selectivities.

Heteroionic sorbents show a high affinity towards polar molecules (H_2O, NH_3, H_2S, SO_2) as compared with non-polar sorbates (O_2, CH_4). This affinity can be ascribed in part to ion-dipole interactions. Heteroionic sorbents also show a pronounced selectivity towards molecules possessing quadrupole moments[27] (N_2, CO, CO_2) as compared with molecules which do not possess significant moments (O_2, A, H_2). Anionic sorbents have a lesser affinity for molecules with either dipoles or quadrupoles, but in this property they are intermediate between the heteroionic and the covalent sorbents. Covalent sorbents such as well-outgassed carbons do not have a very high affinity for water or ammonia, but sorb mainly through dispersion forces, combined with sorbate-sorbate interactions. Dispersion forces are additive and so multi-atomic hydrocarbon molecules tend to be more strongly sorbed than smaller molecules with large dipole moments (H_2O, CH_3OH). The isotherms and isobars for water have already been compared for a zeolite and for a silica gel in Figs. 6 and 7, but the different affinity sequences for these sorbents will be further illustrated with reference to N_2, O_2 and A. Fig. 8[27] shows how much more strongly nitrogen is sorbed at −78°C and 0°C by a faujasite-type zeolite than is oxygen or argon. On the other hand, on a siliceous porous glass[53] or on alumina-silica cracking catalyst[54] there is little distinction between these gases. This is also true of carbon sorbents for the nitrogen-argon pair[55] (here oxygen must be excluded because it can be chemisorbed by carbon). Because of the greater affinity shown towards nitrogen which is common to other zeolites (chabazite,[1] "active analcite",[1] a Ba-zeolite,[7] mordenite,[3] Linde sieve 5A,[28] all at −78°C) a separation of oxygen and argon from nitrogen in air can be visualised. Such a separation of oxygen and nitrogen was indeed readily carried out by fractional desorption from a faujasite-type sorbent.[27]

Even for noble gases there can be useful differences in selectivity as between carbon and some zeolites. Thus in a synthetic Ba-zeolite and in chabazite respectively, at −194.7°C, separation factors of 35-fold and 27-fold were reported for neon enrichment in admixture with helium,[7] as compared with a five-fold enrichment reported for an active carbon.[56] In mordenite and in chabazite the enrichment factors,* η, for several mixtures at −183°C are given in Table 7, and compared with corresponding factors, η', for vapour liquid equilibria.[57] Clearly, aspects of "equilibrium" separations in gas sorption could well be investigated in static sorption beds and in hypersorption systems. Linde sieve 5A has been used very successfully in adsorption chromatographic separation of mixtures of H_2, O_2, N_2, CH_4 and CO at 100°C, all these gases being freely occluded by the zeolite.[58]

(b) Partial molecular sieve action. For a sequence of gases such as H_2, O_2, N_2, A and CH_4 the critical dimensions for penetration into a crystal have been given in Section 4. These are the van der Waals' diameters, and since all molecules are "soft" to some extent they are more accurate as relative dimensions than in an absolute sense. These critical dimensions are sufficiently different to suggest that in squeezing through "windows" little, if any, wider than the molecules themselves there will be penetration into the crystals at different velocities. That this prediction is well founded can be seen from Figs. 9[6] and 10.[44] The first of these compares rates of occlusion of O_2, N_2 and A in levynite at −184°C, and the second gives the rates in Ca-mordenite at −78°C. The ordinate is the ratio of the amount sorbed at time t to the amount sorbed at equilibrium. In the lower temperature system (levynite at −184°C) the small "foot" seen in the curve for argon in particular is due to nearly instantaneously reversible ad-

* $\eta = \dfrac{\text{mol. fraction of } A \text{ in sorbed phase}}{\text{mol. fraction of } A \text{ in gas phase}} \times \dfrac{\text{mol. fraction of } B \text{ in gas phase}}{\text{mol. fraction of } B \text{ in sorbed phase}}$

sorption of about 1 cc at N.T.P. of gas upon *external* surfaces of the powdered crystals. One can expect that if a mixture of argon and oxygen were passed through levynite at −184°C with a contact time of several minutes, at least 99% of the oxygen should be removed. Linde sieve 4A also shows a very great difference in rates of sorption of oxygen and nitrogen at −184°C, the effect being comparable with the differences for oxygen and argon in levynite.

A study of rates of intracrystalline flow in ion-exchanged forms of mordenite[44] led to the results of Tables 8 and 9. In the first of these are compared relative sorption rates of different gases in each of a series of molecular sieve sorbents. The correlation between the relative rates and the critical dimensions is particularly clear both in Figs. 9 and 10 and in Table 8. Table 10 compares the relative rates for a given sorbate in a series of crystalline ion-exchanged mordenites and in levynite. The results in Table 9 are less simple than those in Table 8, since clearly cation radius is not the only important factor. "Ammonium"-mordenite is always higher in the list than would be expected from the diameter of NH_4^+ ions (~2.86Å). However, the ammonium ion may be lost to varying degrees in these studies by dissociation during outgassing and even during preparation, e.g., by a reaction such as:

$$H_2O + NH_4^+ \longrightarrow H_3^+O + NH_3.$$

It has been shown that hydrogen-mordenite is more open than its cation exchanged forms.[59] Also, the position of cations in relation to the windows is of major importance.

Following the demonstration of notable partial molecular sieve activity, mordenites were used in attempts to separate various gaseous mixtures by taking advantage of different sorption rates.[60] A given gas mixture was passed through a short column of the crystals, and the changes in composition measured conductimetrically. Some of the results obtained are summarised in Table 10. The oxygen-argon pair gives a very rapid separation and merits study on a larger scale, for purification of liquid argon. The argon-krypton pair in mordenite illustrates an interference effect. It appears that krypton is preferentially sorbed in interstitial sorption sites near the surface of each crystallite, and so blocks the diffusion paths normally available to argon. Krypton, on account of its greater diameter, diffuses only very slowly.

(c) Total molecular sieve action. Total molecular sieve action is less likely to arise for pairs of small permanent

TABLE 11. Resolutions of Mixtures Using Chabazite

Mixture	Component(s) Sorbed	Conditions and Comments
$CH_3OH + (CH_3)_2>CO$	CH_3OH	As liquid at ~20°C. Rapid and quantitative.
$CH_3OH + (CH_3)_2>O$	CH_3OH	As above
$CH_3OH + CS_2 + CH_3CN + C_6H_6$	CH_3OH, CS_2 and CH_3CN	As above
$CH_3OH + H_2O + CH_3OCOCH_3$	CH_3OH, H_2O	As above
$CH_3OH + COCH_3$ | $COCH_3$	CH_3OH	Sorption via vapour in equilibrium with solution. Complete separation.
$C_2H_5OH + C_6H_5CH_3$	C_2H_5OH	As liquid at ~20°C. Separation slow but complete.
$C_2H_5OH + CHCl:CCl_2$	C_2H_5OH	As above
$C_2H_5OH + CH(CH_3)_2OH$	C_2H_5OH	As above
$C_2H_5OH + C(CH_3)_3OH$	C_2H_5OH	As above
$C_2H_5OH + n-C_7H_{16}$	C_2H_5OH	As above
$C_2H_5OH + H_2O + (C_2H_5)_2O$	C_2H_5OH, H_2O	As above
$C_2H_5OH + CH_3COC_2H_5$	C_2H_5OH	As liquid at 112°C. Separation rapid and complete.
$C_2H_5OH + CH_2Br_2$	C_2H_5OH	As liquid at ~20°C. Slow but complete separation.
$CH_2O + H_2O + CH(CH_3)_2OH$	CH_2O, H_2O	As liquid at ~20°C. Rapid and quantitative.
$CH_2O + H_2O + CH_3I$	CH_2O, H_2O	As above
$CO_2 + CH(CH_3)_2OH$	CO_2	As above. CO_2 initially in solution.
$SO_2 + CHCl_3$	SO_2	As above. SO_2 initially in solution.
$N_2O_3 + C_6H_6$	N_2O_3	As above. N_2O_3 in solution.
$H_2S + C_6H_6$	H_2S	As above. H_2S in solution.
$CS_2 + CH_3COCH_3$	CS_2	As liquid at ~20°C. Rapid and quantitative.
$CS_2 + CHCl_3$	CS_2	As above
$CS_2 + C_6H_6$	CS_2	As above
$CS_2 + N(CH)_4CH$	CS_2	As above
$C_2H_5SH + C_6H_6$	C_2H_5SH*	As liquid at 50°. Partial removal in a week.
$CH_3NH_2 + C_2H_5OH + N(CH_3)_3$	CH_3NH_2, C_2H_5OH	As liquid at ~20°C. Complete removal of both constituents within 16 hours.
$C_2H_5NH_2 + (C_2H_5)_2NH$	$C_2H_5NH_2$*	As liquid at ~20°. Slow but complete separation.
$(C_2H_5)_2NH + iso\text{-}C_8H_{18}$	$(C_2H_5)_2NH$*	As liquid at 180°C. Separation only partial in five days.
CH_3CN + Thiophen	CH_3CN	As liquid at ~20°C. Rapid and quantitative.
$CH_3CN + CH_2Br_2$	CH_3CN	As above
$CH_3CN + CH{\cdot}O + H_2O + n-C_7H_{16}$	CH_3CN, CH_2O, H_2O	As above
$C_2H_5CN + CH(CH_3)_2OH$	C_2H_5CN*	As liquid at 100°C. Separation complete within two days.
$HCl + CHCl_3$	HCl	As liquid at ~20°C. Dissolved HCl removed quickly and completely.
$Cl_2 + C_6H_6$	Cl_2	As above
$Br_2 + CCl_4$	Br_2	As above. Equilibrium separation nearly complete within 16 hours.
$I_2 + CHCl:CCl_2$	I_2*	As liquid at ~20°C. Partial removal within four days.
$CH_3I + C_6H_6$	CH_3I*	As liquid at ~20°C. Nearly complete in 12 days.
$CH_2Cl_2 + CH(CH_3)_2OH$	CH_2Cl_2	As liquid at ~20°C. Rapid and complete.
$CH_2Cl_2 + CH_3COC_2H_5$	CH_2Cl_2	As liquid at 112°C. Rapid and complete.
CH_2Cl_2 + Dioxane	CH_2Cl_2*	As liquid at 112°C. Partial separation in three days.
$CH_2Cl_2 +$ sym-$C_2H_4Cl_2$	CH_2Cl_2	As liquid at ~20°C. Separation complete.
$C_2H_5Cl + CH(CH_3)_2OH$	C_2H_5Cl*	As above
$CH_2Br_2 + iso\text{-}C_8H_{18}$	CH_2Br_2*	As liquid at ~20°C. Separation complete within 12 days.
$CH_2Br_2 + C_6H_6$	CH_2Br_2*	As above
$CH_2Br_2 + CH(CH_3)_2OH$	CH_2Br_2*	As liquid at 112°C. Separation nearly complete within 24 hours.
$C_2H_5Br + C_6H_6$	C_2H_5Br*	As above. Separation complete.
$C_2H_5Br + CH(CH_3)Cl_2$	C_2H_5Br*	As liquid at 97°C. Separation complete within two days.

* Slowly sorbed at room temperature.

gas molecules in which dimensional differences are small than for pairs of larger vapour molecules. Nevertheless, total molecular sieve action is often more and more nearly approached for pairs of gases ($A + B$), where differences in diffusion velocity arise, as the temperature is lowered. The *ratio* of sorption rates tends to vary exponentially with temperature. However, interference effects such as those described for the argon-krypton pair can arise.

8. Separations of Organic and Inorganic Species

Separations of hydrocarbons, drying and super-drying of gases and liquids, and separations of permanent and noble gases as described in Sections 7, 8 and 9 are important examples of the uses of molecular sieve sorbents. Moreover, the uses of these materials may be extended in various directions. Thus, in what were for the most part static systems, the separations of Table 11 were effected using chabazite as sorbent.[4] The molecules of the compounds marked with an asterisk were only slowly sorbed at room temperatures, but sorption can normally be accelerated by raising the temperature. In the table there are examples of separations of mixtures of components all of which can be sorbed, but at differing rates. Typical are: ethanol - *n* - heptane; ethanol - methylene dibromide; methanol-ethyl bromide; acetonitrile-methylene dibromide; and ethylamine-diethylamine. A number of the mixtures resolved are azeotrope-forming pairs, for example, methanol-acetone; ethanol-*n*-heptane; ethanol-toluene; carbon disulphide-acetone.

From the table it can be seen that mono-substituted methanes, in which the substituents are small groups such as $-CH_3$, $-Cl$, $-OH$, $-CN$, or $-NH_2$, are generally rapidly removed, and mono-substituted ethanes or di-substituted methanes with the same substituent groups are slowly removed at room temperature and more rapidly at higher temperatures from admixture with molecules too large to be sorbed within the crystals. Chabazite, as indicated in Table 2, is fairly typical of several zeolites of which an important example is Linde sieve 5A. This zeolite, in general, sorbs the same molecules as chabazite, but in the case of the larger ones does so rather more rapidly. It has also been suggested for the separation of CCl_2F_2 from CCl_3F and $C_2Cl_2F_4$,[61] which could not be effected with chabazite.

A group of separations carried out using Na-rich mordenite is given in Table 12. Again those species which are slowly sorbed at room temperature are marked with an asterisk: separation can be much accelerated by raising the temperature, as shown by the data for acrylonitrile. With mordenite the separations observed are those of simple inorganic species and of mono-substituted methanes with small substituent groups, such as $-Cl$, $-Br$, $-NH_2$, $-OH$, $-CN$, from similarly substituted ethanes, or di-substituted methanes, or other molecules too large to be sorbed by the crystals. Linde sieve 4A behaves very similarly to Na-mordenite.

Ca- and Ba-rich mordenites as indicated in Section 4 and Table 2 are representatives of a slightly less open group of molecular sieves than Na-mordenite. A number of separations effected with these materials are given in Table 13. Good separations of H_2O, NH_3 or HCl were made from typical organic species, a result which should be true also for separations of such inorganic species from any organic molecules.

The results of Tables 11, 12 and 13, as well as those described in Sections 5, 6 and 7, show the power and scope of the molecular sieve method. They indicate that one could quantitatively pick out one kind of molecule after another from a mixture by passing the mixture through columns of different sieves, arranged in ascending order of openness. Hypersorption techniques can also be used to vary the procedure and the scale of the separation, and to transform stepwise into continuous operation. Hypersorption might be operated with double or even with multiple columns of sieve sorbents, as shown recently in work with moving carbon sorbents.[62]

Occasionally examples of poisoning were observed. At 150-200°C pyridine and thiophen deposited carbon on chabazite which impaired its capacity for sorption. Acetone or methyl ethyl ketone prevented or retarded sorption of less polar molecules otherwise sorbed at reasonable velocity. Thus little or no separation occurred with the mixtures $C_2H_5CN + CH_3COCH_3 + n\text{-}C_7H_{16}$; $C_2H_5Cl + CH_3COC_2H_5$; and $CH_2Br_2 + CH_3COCH_3$. The ketones are probably sorbed preferentially just within the crystallite surfaces, but diffuse extremely slowly and block inward diffusion of the other sorbates.

Zeolites can also catalyse decomposition and polymerisation reactions. Nitric oxide can be disproportionated to N_2O and N_2O_3.[63] Substances containing olefinic bonds may sometimes polymerise[47]; and also dehydrochlorination and possibly dehydrofluorination can occur (for example, from $C(CH_3)_3Cl$[47] and $CHFCl_2$[47, 64] respectively). Liberation of hydrofluoric acid has a deleterious effect upon the sorbent. These catalytic properties are themselves of considerable interest, but will not be discussed here.

TABLE 12—Resolution of Mixtures using Na-mordenite

Mixture	Component(s) Sorbed	Conditions and Comments
$CH_3OH+CH_3COCH_3$	CH_3OH*	At 20°C. Slow but complete separation.
$CH_3OH+C_2H_5OH$	CH_3OH*	As above
$CH_3OH+Pyridine$	CH_3OH*	As above
$CH_3OH+CH_2Cl_2$	CH_3OH*	As above
$CH_3NH_2+C_2H_5OH-NH(C_2H_5)_2$	CH_3NH_2* CH_3NH_2*	As liquid at 73°C. Separation nearly complete within 1 day.
$CH_3CN+CH_2Br_2$	CH_3CN*	As liquid at 60°C. Separation complete within 2 days.
$CH_3CN+CH_3COCH_3+iso-C_8H_{18}$	CH_3CN*	As liquid at ~20°C. Separation nearing completion in 14 days.
$CS_2+C_6H_6$	CS_2*	As liquid at ~20°C. Separation partial in 14 days.
$Cl_2+C_6H_6$	Cl_2	As liquid at ~20°C. Separation complete within 2 days.
$HCl+CH_2Cl_2$	HCl	As liquid at ~20°C. Separation complete in less than 12 hours.
$N_2O_3+C_6H_6$	N_2O_3 ($NO+NO_2$)	As liquid at ~20°C. Partial separation in 1 day.
$NH_3+H_2O+C_2H_5OH$	$NH_3.H_2O$	As liquid at ~20°C. Separation complete within several hours.

* Slowly sorbed at room temperature.

TABLE 13—Resolution of Mixtures using Ca- and Ba-mordenite

Mixture	Component(s) Sorbed	Conditions and Comments
$H_2O+C(CH_3)_3OH$	H_2O	As liquid at ~20°C. Separation rapid and complete.
$H_2O+NH_3+CH_3OH$	H_2O,NH_3	As above
$NH_3+C_2H_5OH$	NH_3	As above
$NH_3+C_2H_6$	NH_3	As gas at ~20°C. Separation quantitative.
$NH_3+C_3H_8$	NH_3	As above
$HCl+C_2H_6$	HCl	As above

9. Modification of Porous Crystal Sorbents

A simple way of modifying the openness of molecular sieve and porous crystals has proved to be ion-exchange. Replacement of Na^+ ions by Ca^{++} ions changes the more open faujasite-type sieves, such as 13X, to the less open type 10X and also changes mordenite into a less open structure (cf. Tables 12 and 13 and Section 4). On the other hand, this same replacement converts the less open forms Na-chabazite and Linde sieve 4A to the more open forms Ca-chabazite and Linde sieve 5A respectively. This behaviour does not here depend on cation size, since Na^+ and Ca^{++} have nearly the same ionic radius, nor does it depend through cation valence upon the number of cations present (two Na^+ are replaced by one Ca^{++}). It seems, therefore, that it must depend upon the positions of the cations relative to the windows through which sorbate molecules must diffuse. Cations located in the centres of such windows, for example, could block entry of many sorbates, while cations located elsewhere in the major cavities of the crystals (see Section 2) might permit free entry of these sorbates.

The porous bentonite sorbents in which the exchanging cations are one of the series $CH_3NH_3^+$, $(CH_3)_2NH_2^+$, $(CH_3)_3NH^+$, $(CH_3)_4N^+$ and $(C_2H_5)_4N^+$ also show changes in affinity for a given sorbate due in part to the varying free distance between the alumino-silicate lamellæ which are propped apart by the organic cations.[35] There is a simultaneous tendency for the crystals to become less hydrophilic and more organophilic as the size of the intercalated ions increases.

It is also possible to modify the molecular sieve properties of zeolites by increasing the size of the cations while keeping their valency constant. This method has been studied in considerable detail[44, 68] for the H-, Li-, Na-, K-, and NH_4-, and for Ca- and Ba-forms of mordenite, the salient features having been discussed in Section 9b. Clearly, by such means one may produce various subdivisions of molecular sieve behaviour within the main divisions of Table 2, Section 4. A further procedure which has been successfully employed[65] consists in synthesising a given zeolite with different alumina : silica ratios in the framework. Such a range of synthetic potassium zeolites similar to chabazite was prepared, and then the products subjected to simple cation exchange. This procedure is equivalent to effecting isomorphous replacements of the types $LiAl \rightleftharpoons Si$, $NaAl \rightleftharpoons Si$, $KAl \rightleftharpoons Si$, $RbAl \rightleftharpoons Si$ or $(\frac{1}{2}Ca)Al \rightleftharpoons Si$, in an otherwise largely unaltered anionic framework. Fig. 11 shows the way in which the amount of oxygen sorbed at −183°C and at 20 cm. pressure changed with silica : alumina ratio for the Ca^{++} and Na^+ ion-exchanged homoionic forms. In all these zeolites the power of sorbing water was retained.

Another procedure for modifying the molecular sieve behaviour consists of adding to the crystals controlled amounts of small polar molecules (H_2O, NH_3, CH_3NH_2) which are strongly held and are immobile at the temperature of the subsequent sorption runs.[66] By such means the diffusion coefficients of sorbates within the crystals may be modified progressively and selectively, as shown in Fig. 12, until a point is reached where component *A* is still rapidly sorbed on a convenient time scale, but component *B*, having a larger molecule, is only slowly sorbed.

10. Conclusion

Enough has been said to demonstrate the effectiveness of porous crystal sorbents in the field of selective sorption. Porous crystals provide new kinds of sorbent materials with capacities as good as those of amorphous and non-porous crystalline sorbents hitherto employed industrially or in the laboratory, but with the additional molecular sieve function which introduces a new order of selectivity into sorption processes. The new sorbents can be provided in a range of classes each with a different molecular sieve character. For an appropriately chosen sieve sorbent quantitative separation can often be achieved in a single act of sorption. This opens up new possibilities for selective sorption by molecular sieve action as a unit engineering process.

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CORROSION TESTING IN CHEMICAL PLANTS

Plant corrosion tests are a guide to the selection of constructional materials. Techniques for measuring corrosion are discussed

by R. S. THORNHILL, M.A., Ph.D., F.I.M.

THE technical expert concerned with corrosion problems in industry is faced with two tasks. First, he must assess the extent of corrosion and decide its seriousness in the light of the metal thickness and expected life of the plant, or of other factors, such as the purity, colour of the product or safety of personnel. He must also find an explanation for the corrosion, carrying out such experiments as are necessary to that end. Secondly, he must advise on methods of overcoming or limiting the attack. This may involve tests on alternative materials of construction, surface coatings, electrical methods of protection, such as cathodic protection, or of modifications of the environment.

Although laboratory services are indispensable in corrosion work, and much can be learnt from laboratory tests, the experimental conditions may be so difficult to reproduce in the laboratory that it is often quicker and more satisfactory to perform all the tests on the plant. It is the purpose of the article to discuss some of the techniques employed for measuring, elucidating and combating corrosion in chemical plants.

Detection of Corrosion

The fact that corrosion is taking place in a plant may become apparent in various ways. For example, plants are taken off work at regular intervals for overhaul and maintenance, and it is during this time that corrosion damage is carefully sought. It is also usual in many industries to analyse the products for metallic impurities, notably those from which the plant is constructed. A rise in concentration indicates a loss of metal somewhere in the system, but will not, however, show whether the attack is localised or general. Also, where heating or cooling is carried out, in heat exchangers, evaporators, etc., it is usual to test for contamination of one medium by the other; contamination does not necessarily denote corrosion, but it indicates direct contact of some kind between the two sides of the metal. More obvious signs of corrosion damage are leaks (from vessels), loss of power (from pumps in the last stages of disintegration), increase in pressure drop (in tube bundles) and mechanical failure.

To help in locating attack when observation is difficult, the Introscope is often useful. It is employed primarily for examining tubes, and is a telescope fitted with a light source at the eye-piece end and a 45° prism beyond the

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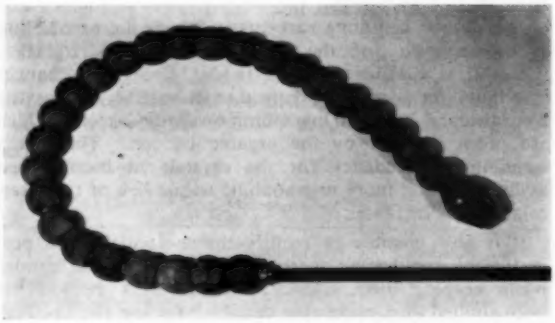

Fig. 1. *Eddy current tester adapted for boiler tubes.*

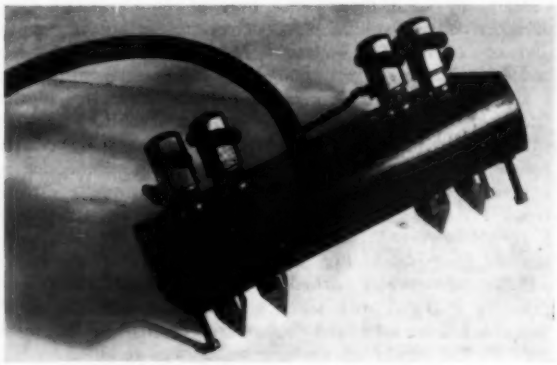

Fig. 2. *Direct-current thickness tester.*

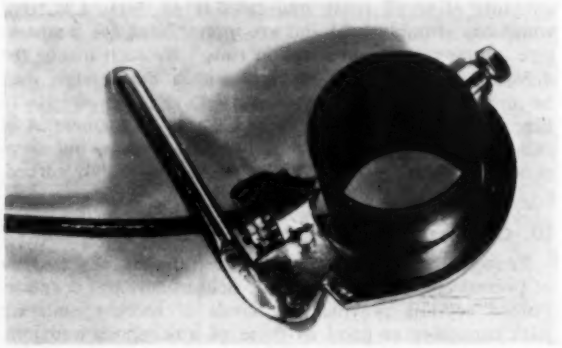

Fig. 3. *Direct-current thickness tester adapted for tubes.*

Fig. 4. Magnetic permeability instrument for measuring thickness.

Fig. 5. Ultrasonic thickness tester.

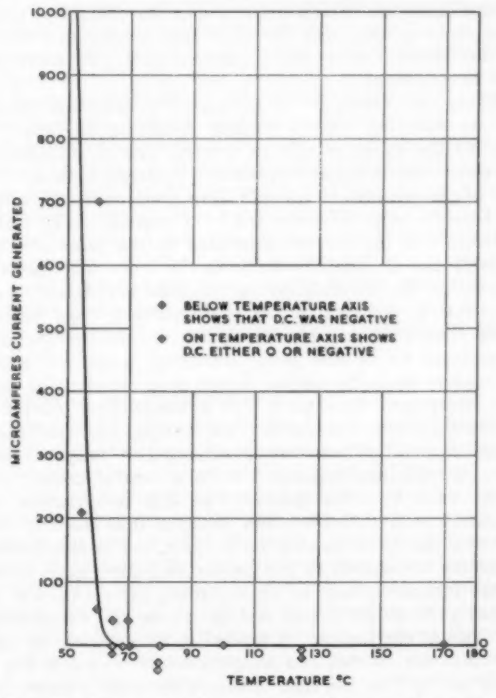

Fig. 6. Curve showing relation between corrosion current and temperature for the bimetallic probe.

objective. It can be obtained in different lengths, and gives a high-lighted view of the surface under examination.

Instruments based on eddy currents have been developed which measure the thickness of non-magnetic materials and hence will detect corrosion pits. An early form[1] consists of an iron core on which are mounted insulated frames, carrying a primary and two secondary coils. The secondary coils are in series with a metal rectifier and microammeter, and are so positioned that when the core is energised with a.c., only a slight out-of-balance current flows through the microammeter. When the iron core is brought up to the surface under test, eddy currents are set up in the material which disturb the balance between the two secondary coils, and this is registered on the microammeter. The relation between current and thickness of metal can be established by calibration. A modification of this instrument for the specific purpose of locating pits in boiler tubes is shown in Fig. 1.

The Probolog[2] and Introview are versions of the eddy current instrument, which give continuous records of metal wall thickness as the exploring head is moved down a tube by mechanical means. The instruments are designed for the rapid examination of large numbers of tubes in condensers and coolers, and besides indicating the number and magnitude of the irregularities will also demonstrate changes in composition arising from corrosion, e.g., the dezincification of brasses.

The routine examination of structures for cracking can be a long and arduous task. In the first instance, cracks are usually picked up by inspection or by leakage. Cracks induced by stress-corrosion will occur where stresses are to be found. This may be in riveted seams, non-stress-relieved welds, deformed structures, rapidly heated or cooled surfaces, or in members where vibratory movements are present. One method of examination, suitable for ferritic materials, is to magnetise the surface with a powerful horseshoe magnet, and spray with a magnetic ink. If the surface has been painted white before magnetisation, the cracks show up as dark lines on a light background.

Ultrasonics are now extensively used for crack detection, and are not limited to ferrous metals. A series of impulses is sent through the material from a quartz crystal, and echoes from reflecting surfaces, which will include cracks normal to the beam, are picked up and registered on an oscillograph screen as a series of "blips". In one model the same crystal is used for both transmission and reception, while in another two crystals are employed. Considerable skill is needed in the operation of these instruments to avoid spurious echoes.

Measurement of Corrosion

If the corroded surface is accessible from both sides, thickness measurements can be made with a micrometer screw gauge or vernier calipers. Ball- or cone-shaped end pieces increase the accuracy of measurement, and for pits depth gauges are useful.

Where it is not easy to reach both sides, various other expedients can be adopted. One is to drill a test hole, but if the tester is working blind it is possible for a corroded area to be missed. On new structures, where wall thickness is important, test plugs of known length can be introduced through the walls before the unit goes on work.

For measuring the internal bore of tubes, gauges operating on the "go no-go" principle have proved highly satisfactory. A set developed for measuring the change in bore of heat-exchanger tubes due to corrosion was made from steel rods, into the ends of which on opposite sides two small pegs were brazed. The pegs were ground down until the distance across covered the range 0.620 in. to 0.655 in. in increments of 0.005 in.

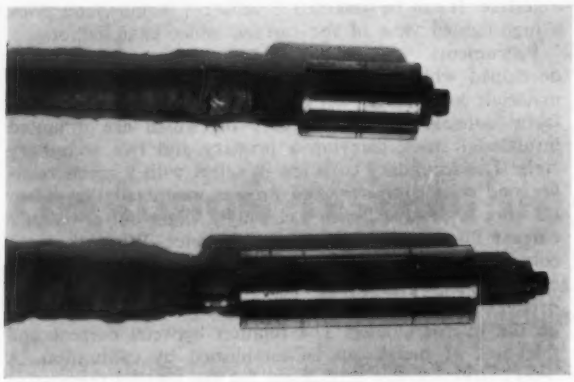

Fig. 7. Illustration showing (top) bimetallic and (bottom) corrosion probes before use

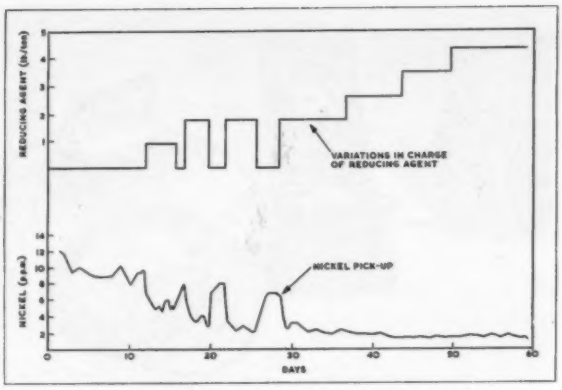

Fig. 8. Variation in nickel pick-up by caustic liquor with charge of reducing agent.

A number of instruments is available for thickness measurement from one side only. Some will function satisfactorily when the units are on work; others require clean surfaces, or are usable only in the cold. Equipment commonly used is based on (a) d.c. resistance, (b) magnetic permeability, (c) ultrasonics, and (d) eddy currents, as already described.

In the d.c. resistance device, a heavy current derived from a 12-volt car battery is passed through the metal between two centres 8 in. apart, and the potential between two inner points is measured on a millivoltmeter. The applied potential difference, and hence external current, is varied until the millivoltmeter reads some agreed figure, nearly to the edge of the scale; then, from a calibration curve between the applied current and plate thickness, the unknown distance may be read off. It has been shown that if the distance between the outer electrodes is greater than six times the thickness, the calibration curve is a straight line passing through the origin. Hence, to calibrate on a structure it is only necessary to fix one point—at a place where the thickness is accurately known or can be measured by some other method. The position of the calibrating line depends on the material; for wrought iron and mild steel the same line can serve, but cast iron gives varying results according to its structure and degree of ageing. Calibration must therefore be carried out on the item itself. A photograph of the instrument and an adaptation for dealing with tubes are shown in Figs. 2 and 3. If the diameter of the pipe is more than 4 in., the same calibration curve can be used as for flat plates. This type of instrument is useful for metal thicknesses from $\frac{1}{4}$ in. to $1\frac{1}{2}$ in., and is accurate to about 10%. It functions when the metal on the reverse side is covered with corrosion products or scales, but is adversely affected by thermoelectric currents, and cannot, therefore, be used on equipment holding hot materials.

The magnetic permeability instrument, illustrated in Fig. 4, consists of a portable horseshoe magnet, which can be energised by coils wound round each pole piece. The test head is put on the material under examination, which forms the keeper of the magnet, and the magnetic field is established for two minutes by pressing a switch. The latter is then released, and the flux is taken up by the coils and transmited to a ballistic milliammeter. The current is dependent on the thickness of the metal, which can be measured to an accuracy of 2%. It is suitable for iron up to thicknesses of 0.4 in.

The ultrasonic equipment, like the crack detectors, depends on the transmission of vibrations through the material from a quartz crystal. In one instrument (Fig. 5) the frequency of the vibration is increased until resonance is obtained between the outward and reflected signal, and this is indicated by the position of maximum noise on headphones. The thickness can be found from calibration curves, or if the fundamental frequency is known it can be calculated, since it is exactly half the wave length. These instruments can be used quite satisfactorily with hot metals, but fail when the far side is covered with heavy deposits, due to absorption and dispersion of the vibrations. Internal damping makes lead a difficult material to investigate.

Galvanic Corrosion

It may be necessary to discover whether under working conditions a metal is corroding because of contact with some other metallic material of a more noble character. If it is possible to make a physical separation of the materials during a suspension of work, it is merely necessary to make connections by wires to a milliammeter or millivoltmeter. A better measuring instrument is the zero-current ammeter, which ensures that no current is taken from the assembly, and therefore that polarization effects do not vitiate the results. High-resistance voltmeters can also be employed.

Where the dissimilar metals cannot be separated, pieces of one material, with a surface condition as nearly as possible the same as that in service, can be attached to the other with a suitable insulating material between.

It is also possible to gather information about the attack on a metal if it is connected to a second, more noble, material, and the current generated by the bimetallic cell so produced is suitably measured. In order that the base element of the cell shall not be corroded appreciably more by coupling, the area of the noble element must be kept small. This principle has been used to indicate the temperature to which flue gases containing water and oxides of sulphur could be cooled before they attack mild steel. The instrument developed[3] was a steel-copper couple in cylindrical form, with internal air cooling. The steel specimens consisted of two tubular sections $\frac{3}{4}$ in. long, mounted on a spindle, and separated from a central copper ring $\frac{1}{16}$ in. thick by mica spacers. The skin temperature was measured with thermocouples soldered into the two steel sections, the wires passing via a cable to a millivoltmeter, while the conections to the copper and steel were carried to the measuring box by an adjoining cable. Air was admitted at 60-80 psi at one end by a hose and escaped into the flues at the far end. A typical curve showing the relation between current and temperature is shown in Fig. 6, while in Fig 7 on the right is shown the couple before use. On the left is illustrated a "corrosion probe", which consisted of a single steel cylinder, weighed beforehand,

enclosed between two guard tubes, and cooled in the same way. The results obtained with the corrosion probe agreed to within a degree (°C) with those indicated by the bimetallic probe, but required eight hours to obtain a reasonable loss of weight, whereas the "bimetallic probe" gave an answer in a few minutes. The field of application of this type of instrument is to determine the corrosive properties of hot gases.

Electrode Potential Measurements

In laboratory experimentation the potential difference between a metal and the liquid in which it is in contact is frequently employed to study the formation and breakdown of surface films, and the subsequent corrosion behaviour. These potential differences cannot be measured individually, but have to be combined with a second metal/liquid combination to form a bimetallic cell, whose potential difference can then be measured. The second half cell must be stable and reproducible, since it is to be the reference against which the unknown potential is measured. A convenient combination is clean copper in contact with a saturated solution of copper sulphate, the whole contained in a cylindrical ebonite tube fitted with a porous wooden plug in the bottom. To make a potential measurement a wire connection is taken from the material under test to one side of a high-resistance voltmeter, and from the other side to the electrode of the half cell. The circuit is completed when contact is made between the copper and the metal under test through the surrounding electrolyte, via the porous plug and the copper sulphate in the half cell. Potential of metals can be measured against natural and sea water, plant liquors and soils. Measurements on non-conductors, dry surfaces or very thin moisture films are not possible.

When the metal and electrolyte are accessible, measurements can be made without difficulty; in the case of an enclosed vessel containing liquid, a reading can be obtained by pushing the half cell through a valve below liquor level, so that the porous tip is in line with the surface. A less accurate method is to run the liquor out slowly through a tap into a bottle containing the half cell. To ascertain the effect of liquor composition down a stripping column on the corrosion potential of a metal, samples of liquor can be run from various levels into a bottle containing the half cell and the metal under test.

Potential measurements are used extensively in cathodic protection surveys. This method of protection aims at opposing the corrosion process by sending current into the corroding material from an outside source. The electrical connections are in the same direction as in electroplating, and protection is achieved when the surface is maintained at some accepted potential relative to the standard. The accepted figure for mild steel and cast iron in soils and electrolytes is 0.85 to 1 volt negative to the copper sulphate half cell.

Control of the Environment

Although it is theoretically possible to get an idea of the rate of metal corrosion by measuring the rate of hydrogen evolution or the disappearance of a depolariser, such methods are infrequently used in industry. It is much more common, in both batch and continuous processes, to analyse the product for its metal content, and from the result to calculate the loss of thickness of the unit concerned. With continuous working it is also possible to observe the effects, beneficial or otherwise, of chemical treatments. To illustrate this point, Fig. 8 shows the effect of adding a reducing agent to a caustic liquor on the pick-up of nickel from the containing vessel. It will be noticed that the nickel in solution varies in phase with alterations in the rate of addition, and at high rates is brought down to a fairly low constant figure. It should, however, be remembered that the level of metal contamination is no guide to the intensity of attack, and one can only ascertain whether or not the attack is uniform by visual inspection of the equipment when it is off the line.

Test Rigs

It is frequently necessary to measure local corrosion rates in various parts of a plant, and to this end it is convenient to devise special test specimens. For example, tapered ferrules fitting into the ends of tubes can be used to study tube-end attack.

Another specimen, shown in Fig. 9, was made for investigating the corrosion of ducting by hot gases containing corrosive condensibles. The rectangular plate fitted over a hole in the ducting and was subject to conditions on the wall, while the disc served to indicate attack by the gas itself at the ambient temperature.

Various expedients may be necessary to introduce specimens into closed systems. Specimens can be made to fit seatings for thermometer pockets, or attached to blank flanges on to mains at L or T junctions. Rod-type specimens can also be introduced into vessels if a valve is available, which can be fitted with a short length of metal tube. If the specimen carries a stout bung which can be pressed into the end of the tube, it can be pushed through the open valve with no loss of liquor from the vessel.

When it is necessary to test a number of materials at the same time, a spool or similar device is employed. Specifications covering a suitable design have been incorporated into A.S.T.M. Standards.[4] A spool used by the author, shown in Fig. 10, uses plate and 3-in. round bar. The thickness of plate is not critical, but it should be stiff enough to withstand movement of the liquor or gas. The specimens may be mounted on steel or other rod, with spacers of insulating material resistant to the conditions. The assembly as a whole may be suspended from wires, or, if there is likely to be much agitation, attached to brackets.

Where access to the corrosive conditions is limited, say through a narrow hole, the type of spool shown in Fig. 11 has proved useful. In this case the specimens were machined from rod and tube to a little less than the diameter of the spacers and slid on to the centre supporting spindle. This type of spool has been employed in high-pressure reactors.

With the previous two kinds of spool, general and pitting corrosion is easily revealed. An alternative device which brings out crevice corrosion is shown in Fig. 12, and consists of two Tufnol lids with recessed holes to take specimens in round bar form. It is intended to be attached to blank flanges.

An ingenious method of assembly described in the literature[5] is to prepare the specimens in the form of strips threaded on two cords, with a glass bead between each specimen. This device has been used for tests in H_2S atmospheres.

Four types of specimens suitable for testing susceptibility to stress corrosion are shown in Fig. 13. In all of these the stress tends to relax as the specimen cracks. Assembly (d)[6] has recently been described for investigating sulphide cracking, and consists of a slotted stainless-steel tube (18 Cr/8 Ni/3 Mo) through the holes in which strips of metal are passed and bent downwards by grub screws. The stress is calculated from the deflection.

Choice of Materials

It is usual to make a preliminary test of a limited number of common materials and subsequently elaborate on those showing the most promise. A preliminary test would

include (1) mild steel, (2) cast iron, (3) copper, (4) aluminium, (5) lead, (6) nickel and (7) 18 Cr/8 Ni austenitic stainless steel. The next exposure might consist of variations as shown below.

(1) The chromium-copper alloy Cor-Ten,* or any of the large number of alloy steels, if high strength or creep resistance is required.

(2) Cast irons in which the form of the graphite has been modified, by suitable treatment, e.g., the nodular and Meehanite* irons. Highly alloyed irons also play an important part in chemical plant, and a test should include the nickel cast irons (Ni-resists*), silicon iron and the nickel-silicon irons (Nicrosilals*).

(3) Varieties of copper are electrolytic, tough pitch and phosphorus deoxidised, with and without arsenic. Alloys with (a) zinc (up to 40%), if necessary containing arsenic to reduce dezincification, (b) tin and aluminium (the bronzes), (c) with nickel (the cupronickels, with and without further additions of iron) are worth trying, if copper has a reasonably satisfactory performance.

(4) Alloys of aluminium with (a) magnesium (up to 7%), (b) manganese (up to 1.5%), (c) silicon (up to 8%) and (d) copper (up to 4%). It is important to check susceptibility to stress corrosion cracking.

(5) Harder varieties of lead containing traces of copper and tellurium, and antimonal lead (up to 35% Sb) are available.

(6) Nickel-base alloys such as Monel* (70 Ni/30 Cu), K-Monel,* carrying about 4% aluminium, S-Monel,* with 4% Silicon, and H-Monel,* a casting alloy containing 1.7% Silicon. Inconel* (80 Ni/13 Cr/7 Fe) has good corrosion resistance, and is available in cast or wrought form. A similar alloy, stiffened with titanium carbide for the purpose of resisting high-temperature creep, is Nimonic 75. Also in the same family are the Nimonics* F, 80, 90 and 100.[8]

A series of nickel-base alloys with rather less nickel are the Langalloys.* The following are their approximate compositions:

Composition of the Langalloys

Langalloy	Ni	Mo	Cr	Fe	W	Cu	Si
4R	63	30	—	5	—	—	—
5R	56	17	15	5	5	—	—
6R	85	—	—	—	—	3	10
7R	56	6	23	5	2	6	—

(7) There is a very considerable variety of stainless steels to choose from. In the non-molybdenum bearing range, steels are available with chromium and nickel contents 18/8, 19/9 and 19/10, with and without titanium or columbium, which stabilises against "weld decay". An extra low carbon grade is also manufactured. Greater corrosion resistance towards chlorides is conferred by molybdenum additions,

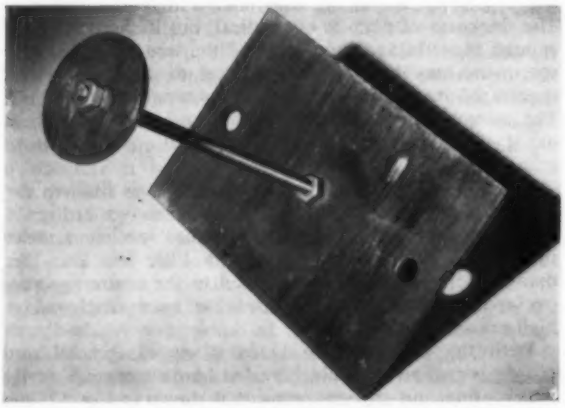

Fig. 9. Specimens for investigating corrosion of ducting.

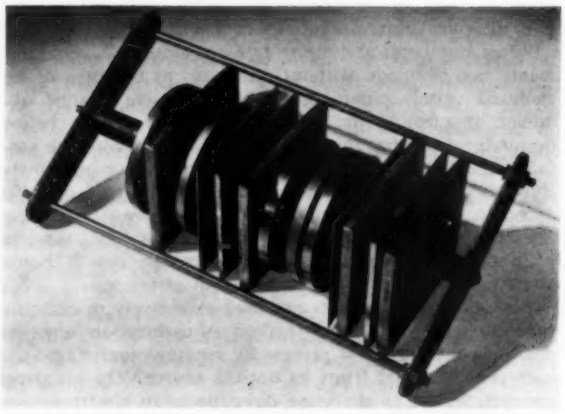

Fig. 10. Assembly of materials for spool test.

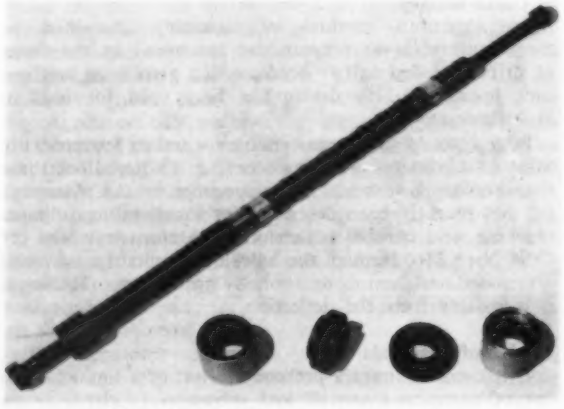

Fig. 11. Spool for pressure vessels.

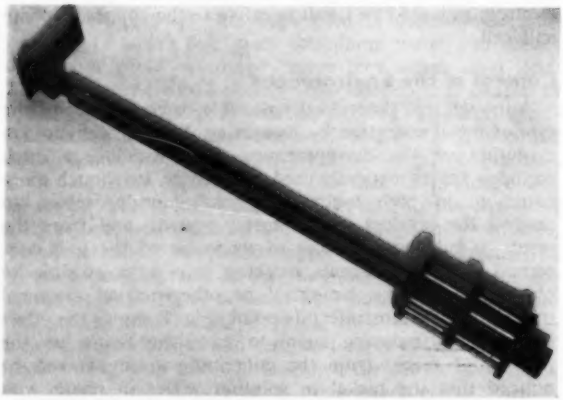

Fig. 12. Test probe with cylindrical specimens.

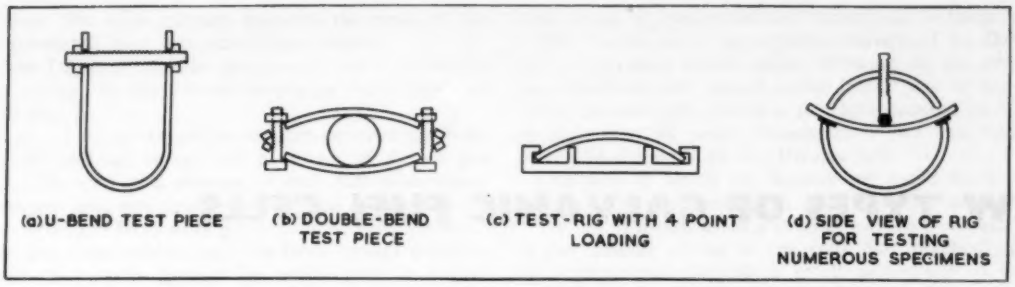
(a) U-BEND TEST PIECE
(b) DOUBLE-BEND TEST PIECE
(c) TEST-RIG WITH 4 POINT LOADING
(d) SIDE VIEW OF RIG FOR TESTING NUMEROUS SPECIMENS

Fig. 13. Four types of specimen suitable for testing susceptibility to stress corrosion.

and steels are available with contents up to 3.5%. Other alloys with greater corrosion resistance are those of nominal composition 18 Cr/18 Ni/3.5 Mo/2.5 Cu and 25 Cr/23 Ni. The alloy containing 18 Cr/2 Ni is also well known, as well as many straight chromium alloys possessing heat- and corrosion-resisting properties. The catalogues of manufacturers should be consulted for special-duty alloys.

This list does not exhaust all the possible metals and alloys that may be tried, but increase in corrosion resistance generally goes hand in hand with cost. Titanium is worth including in any test where chlorides are present, and may be economic because of the relatively high strength and low density. Zirconium may also be investigated where severe conditions are encountered. Magnesium and zinc do not feature to any great extent in chemical plants as a material of construction, but the latter, and aluminium, can be fitted into a test programme in the form of coatings on steel. Chromium, nickel and lead may also require to be tested in the form of coatings.

It must be remembered that the materials mentioned above should be put into the tests in the condition favouring the maximum corrosion resistance. Also, consideration should be given to the form in which the material will be required, e.g., cast, wrought, forged, while differences in casting techniques may need to be compared. If welding is to be used in the construction, a band of weld metal can be laid across the specimen. It may further be necessary to compare welds made with different rods. The disc or plate type of spool is best fitted for this kind of test.

Conduct of Tests

When a number of metals are to be investigated in liquid media, it is advisable not to mix noble and base metals on the same spool, unless it is intended that they should be tested in contact. This is because traces of noble metals taken into solution may deposit on adjacent members of the spool, and set up localised galvanic corrosion. Unless the contrary is desired, specimens should be electrically insulated; bimetallic pairs can be prepared by joining adjacent plates with a tightly-fitting screw.

The ratio of the areas of dissimilar metals in a joint assembly should be accurately known, and if a problem of this kind is being investigated the ratio should be the same as in practice.

The surface preparation of the specimens will depend on the purpose of the test; if it is intended to compare material compositions, a standard finish should be adopted, such as polishing with emery paper, surface grinding, shaping, finishing or turning.

On the other hand, most materials of construction are put into service without any special surface preparation, and it is advisable also to include specimens carrying their natural "as received" finish. For example, in connection with the use of steel, it may be necessary to know whether mill scale gives rise to localised attack and in service would have to be removed.

Specimens should be identified by a method which will not be obliterated by corrosion; stamping is not satisfactory, and it is better to work out a system of notches or drill marks.

The duration of the test may be a matter of choice, but quite often it is only possible to install specimens and inspect them at times of plant overhaul. Short time tests may give a false impression of material performance, if the corrosion-time curve is other than linear.

The cleaning of specimens should be carried out by methods which remove the minimum of metal. Initially, brushing under the tap with an abrasive material is quite satisfactory for all but soft materials. For these and refractory deposits, chemical cleaning methods must be adopted, carrying out a parallel treatment on clean material to discover what weight correction to apply for attack by the pickling agent. The usual acid pickle for many metals is hydrochloric acid containing an inhibitor, adjusting the acid concentration, time and temperature in accord with the refractory nature of the deposit. Sulphuric acid or phosphoric acid pickling is possible, except where the deposit or scale will lead to insoluble sulphates or phosphates. For some scales, which are only slowly soluble in acids alone, additions of bromine or hydrogen peroxide are beneficial. Nitric acid is useful where the material will form a protective oxide film. Another line of attack is to use pickling agents with reducing properties, i.e., molten caustic soda at 350°C containing 2% sodium hydride. Details of suitable solutions and current density for electrochemical reduction of corrosion products will be found in the literature.[7]

The usual method of expressing corrosion rate is as mg/dm²/day, mm/yr or in./yr. The units are readily convertible, but it is advisable to restrict the latter to lengthy tests, or indicate the fraction of a year that the test ran. Penetrations worked out in this way should be supplemented by indications of maximum pit depth, determined by other means.

The preliminary assessment of attack by loss of thickness or weight should be followed by sectioning and microscopic examination to look for signs of selective corrosion, intergranular or transgranular penetration, sub-surface attack and so on.

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621 . 351

NEW TYPES OF GALVANIC FUEL CELLS

Direct production of electrical energy from fuel and the advantages in so doing are discussed by the author

by J. F. STRAATMAN, Ir. (Delft), A.T.I., F.I.L.

THE galvanic fuel cell is a kind of primary battery. It converts into electrical energy the chemical energy liberated by such reactions as:

$$C + O_2 = CO_2 \quad \ldots.(1)$$
$$2CO + O_2 = 2CO_2 \quad \ldots.(2)$$
$$2H_2 + O_2 = 2H_2O \quad \ldots.(3)$$
$$CH_4 + 3O_2 = CO_2 + 2H_2O \quad \ldots.(4)$$

and in their latest forms they do this with an amazingly high efficiency, of 65% or even up to 80%. Were one to use the same reactions to generate electrical energy by conventional means (via steam boiler plus turbo-alternator, or via I.C. engine plus generator) one could not obtain an efficiency much more than 35%. On the other hand, galvanic fuel cells, like all primary batteries, generate DC and not 3-phase AC. This is a minor drawback.

The history of fuel cells started in 1802 with the DAVY cell[1] which uses the oxidation of carbon by nitric acid. The GROVE cell[2] of 1839 was the first to use gaseous fuel, in this case reaction (3). Since then and up to World War II numerous variants, based upon reactions (2) to (4) or combinations of them, have been developed but have not found practical application.

In 1946 the Russian scientist DAVTYAN[3] published details of his high-temperature cell. He was followed in 1957 in the United States by the National Carbon Co.[4] with an ambient temperature cell, whilst the Dutch scientist BROERS[5] followed in 1958 with another high-temperature cell.

The NCC cell, shown in principle in Fig. 1, is the simplest. The electrolyte, a strong solution of potassium hydroxide, is contained in an air- and liquid-tight box, through which run two tubes of porous, specially treated carbon. The tube through which oxygen gas flows is the cathode, the other tube, through which hydrogen flows and through which the product of reaction (3), namely water, is eliminated, is the anode.

If the current density is not too high, the cell delivers current at about 1 v, and to obtain 1 kW one would need such a number of cells that they would occupy 1 cu. ft. This NCC cell can be used only with reaction (3), because any fuel containing carbon compounds (like CO or CH_4) would give CO_2 as one of the reaction products and would spoil the electrolyte through formation of K_2CO_3 and even $KHCO_3$. The high cost of its raw materials (pure oxygen and pure hydrogen) makes its use generally prohibitive. The present application of the NCC cell is to provide current for portable radar sets suitable for use in

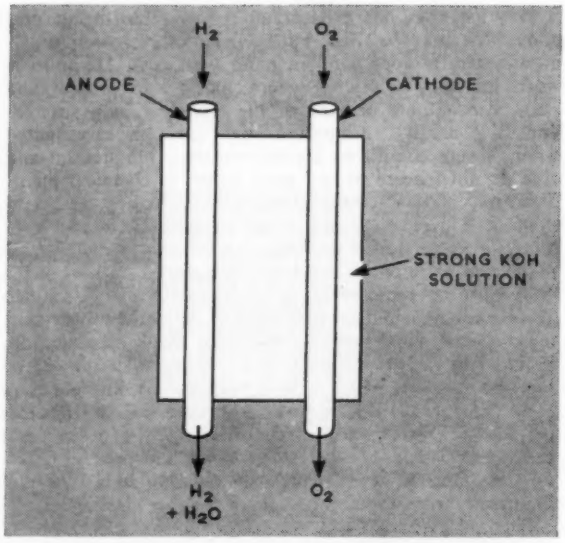

Fig. 1. Diagram of the National Carbon Co. fuel cell. This cell uses the combination hydrogen and oxygen as its energy source.

Table 1

	I	II
Temperature of cell and of converter	720°C	720°C
CO content of gas entering anode room	75%	75%
CO content of gas leaving anode room	10%	20%
Voltage per cell	0.72 V	0.60 V
Amps. per sq. in. of active disc surface	0.13	0.26
Thermal efficiency (not taking into account the exhaust boiler)	66%	52%
Area of active disc surface per kW	75 sq. ft	44 sq. ft
kW per cu. ft	0.24	0.40

any climate. For such military purposes the price of the current generated is of secondary importance.

Both the DAVTYAN and the BROERS cell are very similar in construction. In their most simplified form they are shown in Fig. 2.

A stream of air, or oxygen, or oxygen-enriched air flows through the cathode space, and a stream of a fuel gas (H_2, CO, CH_4, etc.) or a mixture of such fuel gases (town gas, producer gas, gas from underground gasification of thin coal beds, gas from total gasification of coal, methane extracted from coal mines, methane from sewage purification plant, etc.) passes through the anode zone and takes with it the products of the reaction (H_2O and CO_2). Both the cathode and the anode are porous metal plates in most intimate contact with the disc electrolyte. Insulator rings are made from asbestos (DAVTYAN) or mica (BROERS).

In the DAVTYAN case the disc electrolyte is prepared by baking a mixture having, for example, the following composition:

43% calcined Na_2CO_3;
27% Ural monazite sand;
20% WO_3; and
10% "soda glass" (probably sodium silicate).

DAVTYAN claims that, at the operating temperature of his cells, these disc electrolytes are solid. It has been shown, however, by BROERS[6] that at this operating temperature the discs consist of a solid carrier framework of CeO_2 and other oxides of the rare earth metals, impregnated with molten salts such as phosphates and tungstates.

To manufacture his electrolyte discs, BROERS first bakes a porous (70% porosity) disc of sintered magnesium oxide, which he then impregnates with a mixture of molten alkali carbonates; in this mixture the proportion of sodium, potassium and/or lithium carbonate are so chosen that the melting point of the mixture is below the operating temperature of the cell. Clearly, eutectic mixtures give the best results.

Making the cathode and anode is no simple matter. For his anodes, DAVTYAN uses a mixture of 60% Fe_2O_3, 20% fine iron powder and 20% clay, and for his cathodes one of 60% Fe_2O_3, 20% Fe_3O_4 and 20% clay. He adds some water, flattens the paste out into sheets which are then perforated, dried, baked and finally polished on the side facing the disc.

BROERS, once he has baked his magnesium oxide discs and impregnated them with the carbonate mixture, first puts a very thin layer of silver powder on each side, using a trace of sodium silicate solution as glue. On top of the silver powder is a thin silver gauze which is kept flat and in position by means of a perforated plate of nichrome steel.

Experimental cells of the DAVTYAN or BROERS type are about 2 in. in diameter, with an active disc surface of some 1¼ sq. in., whilst discs are about 0.15 in. thick.

The BROERS cell is an improved version of the DAVTYAN cell, as practical results show. Working on air and town gas, DAVTYAN cells have a useful life of one or two days, whilst BROERS cells one that can be measured in months, perhaps even in years. Consequently, we can limit our present discussions to the BROERS cell.

One way in which the BROERS cell could work on the reaction (2) on a production scale is shown in Fig. 3.

Oxygen is produced in a gaseous oxygen plant and piped to the cathode rooms of the cells. For practical reasons (to prevent polarisation) a small percentage of CO_2 is mixed with the oxygen at no extra cost. Into the anode room flows the fuel gas as manufactured in the converter, from coal plus part of the waste gas from the anode rooms. Obviously, only part of the waste gases from the anode rooms can be recirculated through the converter and the rest of these gases, still containing a useful percentage of CO, are burned (e.g., with oxygen from the tonnage oxygen plant) and then, because they are very hot, used to generate steam and hence more electricity.

In the converter, the equilibrium:

$$C + CO_2 \rightleftharpoons 2CO \qquad \ldots (5)$$

is established at the temperature at which the converter works (say 720°C). Since the gas from the converter goes to the cell if the temperature of the cell is lower than that of the converter, the equilibrium of reaction (5) would immediately start to shift to the left. Carbon would be deposited on the walls of the anode room, on the anode and on the disc itself. Passages would become blocked, voltage and current density would drop. Hence, the temperature of the cell must be the same as, or, better still, a trace higher than that of the converter.

Any type of coal or coke can be used in the converter provided its surface is reactive enough to establish the equilibrium of reaction (5) during the time taken by the gas for its passage through the converter. Impurities in the coal or coke are insignificant, because the BROERS cell is absolutely insensitive to H_2S and such compounds. On the other hand, the fuel gas, as it comes from the converter and goes to the cell, must be absolutely free from dust. This again prescribes a low velocity of the gas as it passes through the converter.

There are certain obvious alternatives to Fig. 3. One might use air in the place of oxygen to lower production costs. The consequence would be a slight drop in voltage (say about 4%) and a much bigger drop in the current density that could be usefully obtained from the cell. At the other extreme one might continue to use oxygen as in Fig. 3, but work under pressure, at both cell and converter. In this case, a very slightly higher voltage would be obtained, but a much larger current density could be drawn from the cell. Care, however, would have to be

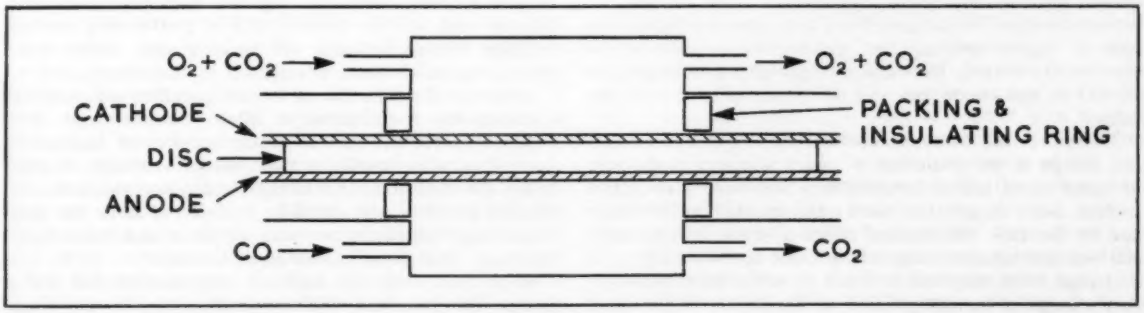

Fig. 2. A simplified diagram of the Davtyan and De Broer fuel cells which use the CO-CO_2 conversion as the energy source.

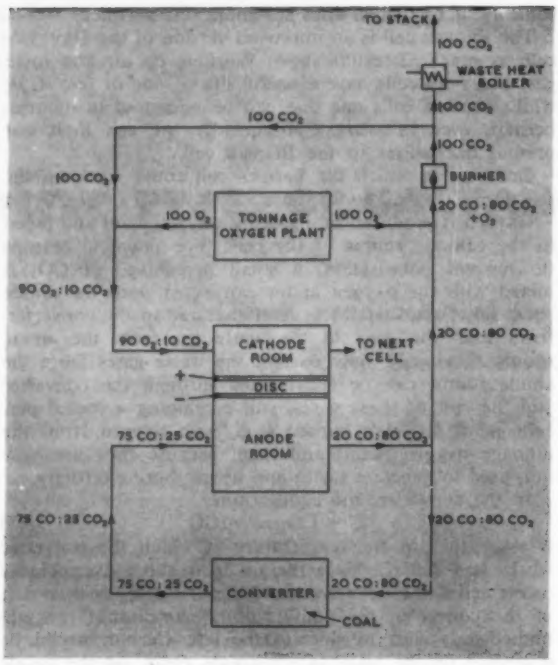

Fig. 3. Flow diagram of a full-scale fuel cell installation based upon the De Broer cell.

taken that pressures in the cathode and anode rooms would be exactly equal, otherwise the discs would soon break. These discs, according to BROERS, are very brittle indeed and there is room for much improvement in their mechanical strength.

Still another alternative would be to inject steam, which is available from the waste heat boiler, into the converter. The fuel gas would then consist of a mixture of CO, H_2 and CO_2. With such a mixture, danger from polarisation of the cell would become less.

A battery of BROERS cells, working in the simplest way possible on CO and air, with re-circulation of part of the waste gas from the anode room, would be described by the figures given in Table 1,[7] in which columns I and II are alternatives and depend on the current density.

In these examples the temperature of 720°C has been chosen as a compromise between two conflicting desiderata. The higher the temperature, the more danger of breaking discs and of leakage. This danger must not be underestimated, because one works on one side of the brittle disc with oxygen or air and on the other side with a highly inflammable gas. It seems imperative that the twain shall not meet. On the other hand, the temperature chosen must be well above the eutectic point of the carbonate mixture. Then again there is a natural desire to go towards higher temperatures, shifting the equilibrium in reaction (5) towards the right, giving higher concentrations of CO in the anode gas and so higher efficiency of the cells.

Therefore, the foremost problem for physicists in fuel cell design is the evolution of much stronger discs, able to stand much higher temperatures and having an active surface much larger than the 1¼ sq. in. used by DAVTYAN and by BROERS. This means either a much stronger (but still porous) sintered magnesium oxide for the carrier, or a change from magnesium oxide to some other material. Any change in the composition of the carrier might entail a change in the electrolyte, say from an eutectic mixture of carbonates to one of phosphates.

Once this main problem has been solved, the other chemical engineering problems would follow: such as how to work at elevated pressures so that pressures on both sides of the disc are absolutely equal; choice of materials for cathode and anode rooms; materials for the rings serving as insulators and as packing; construction of the converter so that the cells would not be contaminated by dust; and the heat-balance between converter and cells. These are only a few of the problems likely to arise.

Their solution would be expensive, but the same could have been said of atomic energy which is now with us. Fuel cells may be a means of generating electrical energy at a much lower cost than by nuclear fission and they have the advantage that raw materials would not have to be imported. Some more research on fuel cells might pay its way very handsomely indeed. BROERS has carried out an enormous amount of fundamental research in his monumental work as well as a very considerable amount of applied research. Now chemical engineering research is needed.

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New U.O.P. Refining Process

"MOLEX", a new process for removing low-octane ingredients from petroleum mixtures, has been developed by Universal Oil Products. Previously the only available method for separating the low from the high octanes was based primarily upon distillation and collection of the vapours, but the technique is both difficult and costly due to the close similarity in physical properties of the straight and branched chain compounds. The new method makes use of molecular sieves, a subject dealt with in detail by PROFESSOR BARRER on page 267 of this issue.

Early tests show the new process to be not only economical but also capable of producing petroleums with octane numbers as high as 105. Further, the process reduces the need for high-octane benzene-type chemicals, which have at present to be used to counteract the low-octane performance of normal paraffins. Consequently, the fuels produced by the molecular sieve process will burn more clearly and high-compression I.C. machinery will perform with greater flexibility.

In addition to providing more economical high-performance automotive fuels, it is expected that the process will open new petrochemical markets to refiners. Adoption of the U.O.P. Udex aromatics separation process (see page 310 this issue) has provided refiners with a method whereby they can separate high purity benzene, toluene and xylene from U.O.P.'s platforming process product. These chemicals will be in greater supply when less aromatics contents is required in fuel blends.

Economical separation of normal paraffins will similarly stimulate the manufacture of other petrochemicals. It is possible, moreover, that abundant supplies of high-purity normal paraffins could be the basis of synthesis of aldehydes, alcohols and other straight chain organic chemicals. Normal paraffins also could be a preferred stock for high-temperature pyrolysis to make ethylene and other intermediates, since paraffins are easily cracked.

Since Universal is a research organisation and not a refiner, the new fuel will be manufactured by petroleum companies in all parts of the world under licences issued by Universal.

ASPECTS OF FLUIDISATION

Abstracts of papers presented at Manchester Symposium

THE North-Western Branch of the Institution of Chemical Engineers held a successful symposium on fluidisation at the College of Science and Technology, Manchester, on March 10. Laboratory experiments on the rise of bubbles in a fluidised bed were described by J. F. DAVIDSON, R. C. PAUL, M. J. S. SMITH and H. A. DUXBURY. The bed was fluidised with an amount of gas just greater than the minimum necessary for fluidisation. Single gas bubbles were produced and rose in the fluidised bed at the same speed as they would in an inviscid liquid of zero surface tension. The gas bubbles were true voids and contained very few particles.

A paper entitled "Thermo-drying in Fluidised Beds" was read by D. W. BEEKEN and was limited to granular materials and to the removal of surface moisture by vaporisation. The maximum particle size can be 1½ in. diameter or more, although in general, ⅜ in. diameter should not be exceeded, but the particle size distribution should be wide and distributed over four consecutive Tyler screens, he said. The behaviour of the fluid bed will vary with the density and with the structure of the material and preliminary, cold fluidising tests should be done on the material. A large air supply is necessary and the air should emerge from the bed about 90% saturated and at nearly the same temperature as the dried product. The fluidised bed is supported on a hearth that is designed to ensure even gas distribution over the entire base of the bed. The gas instantly gives up its heat on entering the bed and one thermocouple indicates the temperature of the properly fluidised bed. New feed soon mixes with the old, nearly dry material and is rapidly dried. A temperature control instrument maintains a pre-set temperature of the bed by regulating the input of fuel to the burner; the air for combustion can be regulated to a constant air to fuel ratio. Hot gases, for example, enter a bed of fine, wet coal at 700 to 1000°F and their temperature drops almost immediately to a safe temperature of 150 to 160°F. When the bed temperature is decreased from 150-130°F, two and a half times as much air for drying may be required. The temperature of the hot flue gases may be reduced between the burner and the bed by cold air or water to a temperature suitable for the material to be dried. A cyclone recovers fine, nearly-dry material from the gases. Large equipment is required to dry fine powders but 2-30% of moisture may be removed by fluidisation of a variety of materials such as limestone, dolomite, blast furnace slag, clay, chemicals and fine coal.

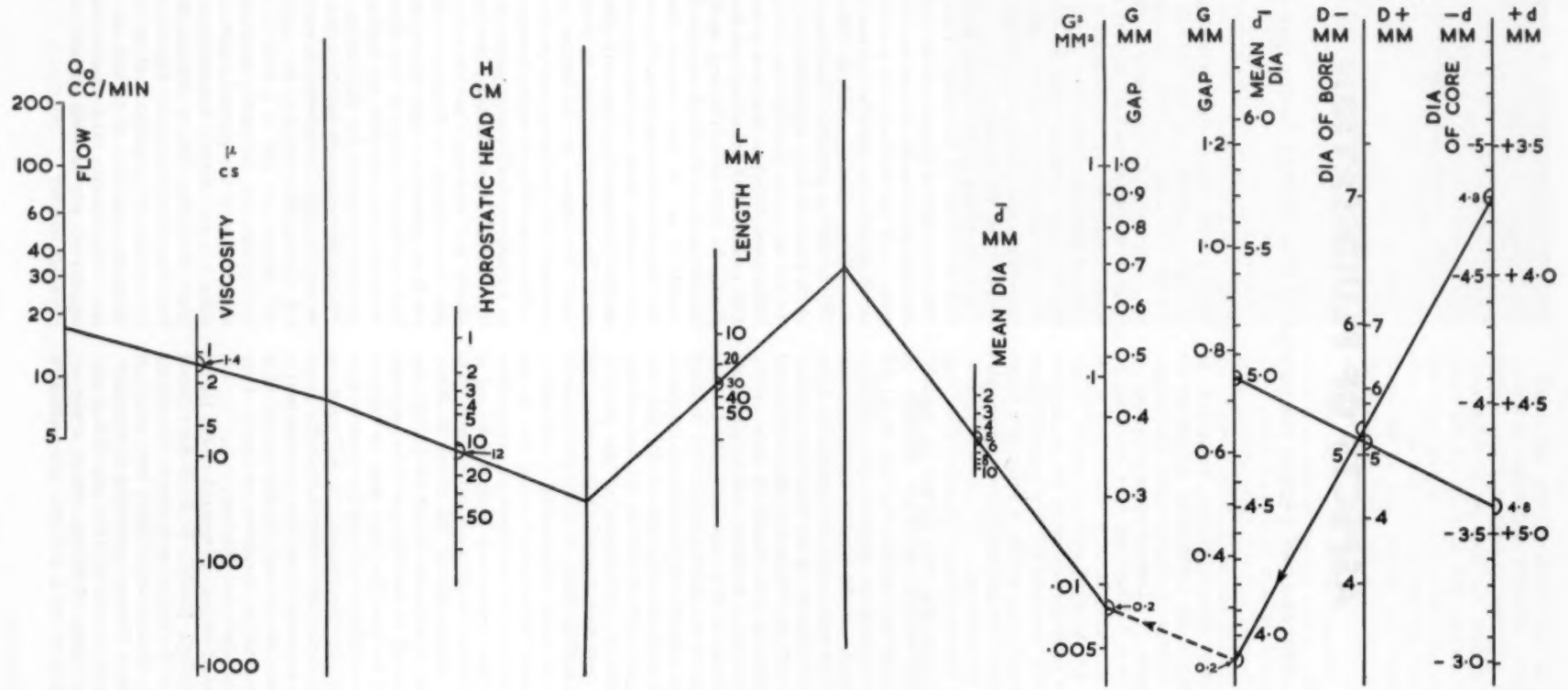
In a paper entitled "Fluidisation Applied to the Handling and Mixing of Bulk Solids", F. E. D'ARCY-SMITH described examples of fluidisation processes in the cement and other industries. One example dealt with soda ash which arrived in railway Covhops containing 17 tons each; the soda ash is emptied in one hour from any of four outlets into a slightly sloping, fluidising trough conveyor, passes into a surge hopper and is delivered into a pressure vessel powder pump which forces the powder in batches through a pipeline by compressed air into a silo for storage or to a service hopper combined with batch weighing equipment. Railway cement wagons discharge powders fluidised by compressed air through pipelines; this wagon is the equivalent of a low-pressure powder pump and conveys powders either over short distances or at low delivery rates. Control panels for the delivery of alumina on a very large scale to storage silos were shown. Success in handling and conveying by fluidisation depends on the properties of the powder.

During mixing by fluidisation the air causes an upward flow of powder at the centre of the bed and there is a downward flow at the sides of the vessel. This movement is disorganised when the air causes 'boiling', but it is maintained until the fluidised state is destroyed by channels of air. Segregation by particle size was illustrated by fluidisation mixing of 40%: 150 to 300μ particles with 60% 300 to 400 μ particles. The finer fraction if fluidised alone would be fully expanded at an air velocity at which the bed of coarser particles had not even begun to expand. Fluidisation failed to mix these powders, but most industrial powders can be mixed satisfactorily but not completely by fluidisation. Mixing by fluidisation is usually carried out in a cylindrical silo, the floor of which is permeable to air. At first uniform distribution of air over the floor area was usual but later one quadrant of the floor received more air than the other three; later silos divided the floor into rings with different air velocities in each. The author considered in detail the mixing of raw meal for cement by fluidisation and by other means resorted to in the interests of perfection or of economy.

The paper "Heat Transfer between Particles and a Gas in a Fluidised Bed" was presented by P. AYERS and J. F. RICHARDSON. In a fluidised system heat can be transferred rapidly to a submerged surface and uniform temperatures can be maintained in all parts of the bed. Although the solids are mixed to a high degree, the back mixing of the fluid is small. If the gas is well distributed at the bottom of the bed and if its flow rate does not greatly exceed the minimum required for fluidisation, intimate contact is effected between solids and fluid, and equilibrium for heat or mass transfer is reached in a very short distance in the bed. During heat transfer, the temperature of the solids will change very little as a result of contact with the hot gas because the volumetric heat capacity of the solids exceeds that of the gas and rapid movement of the particles ensures uniform temperatures in the whole bed, apart from the shallow transfer zone at the bottom. Experiments were made on heat transfer from air or carbon dioxide to a shallow bed of small spheres and the temperature gradient in the bed was measured by a delicate thermocouple. The results were correlated by a logarithmic plot of the Nusselt number against the Reynolds number.

LIQUID FLOW THROUGH AN ANNULUS

by D. WORMALD



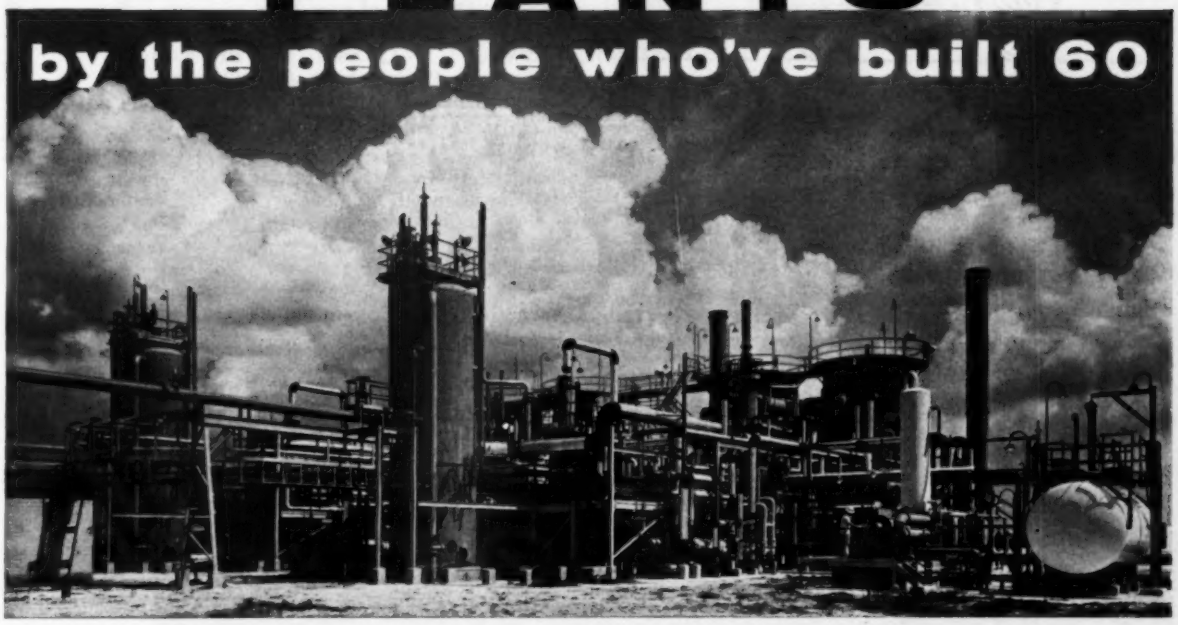
British Chemical Engineering
NOMOGRAM NO. 36

Legend for Nomogram 36 is on page 292

BCE 5269 for further information

AMMONIA PLANTS

by the people who've built 60



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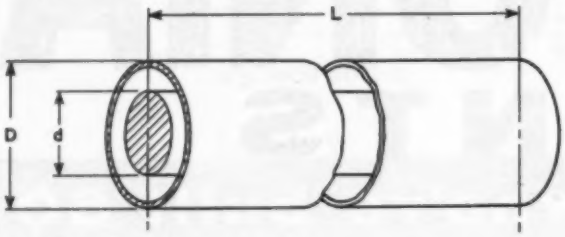
LIQUID FLOW THROUGH AN ANNULUS

by D. WORMALD

This nomogram gives the flow of liquids through a concentric annulus of relatively small gap such as occurs in many nozzles for example.



Formulæ

The following equation often given for the flow of liquid through an annulus:

$$Q_o = \frac{\pi H g}{128 L \nu} (D^2 - d^2) \left[D^2 + d^2 - \frac{(D^2 - d^2)}{\log \frac{D}{d}} \right] \quad \ldots . (1)$$

is not very practical for calculations when the values of D and d are close together. The flow is more readily calculated, as suggested by LEWITT,* from the formula for flow between parallel plates of breadth b, distance apart G, and length L,

$$\text{Flow } Q_o = \frac{H}{12 L \nu} b G^3$$

For an annulus the effective value of b is the mean perimeter, i.e.:

$$b = \pi \bar{d} \quad \ldots . (2)$$

where the mean dia. $\bar{d} = \frac{D + d}{2}$ . . . . (3)

the gap $$G = \frac{D - d}{2} \quad \ldots . (4)$$

hence $$Q_o = \frac{\pi H g}{12 L \nu} \bar{d} G^3 \quad \ldots . (5)$$

if the quantities have dimensions given in the example below, Equation (5) may be written as follows:

$$Q_o = 1540 \frac{H}{\nu L} \bar{d} G^3 \text{ cc./min.} \quad \ldots . (6)$$

Example

Diameter of bore, D =	5.2	mm
Diameter of core, d =	4.8	mm
Length, L =	30	mm
Pressure head, H =	12	cm
Kinematic viscosity ν =	1.4	centistokes
Volume flow, Q_o =	17.6	cc/min.

Use of the Nomogram

Starting with the diameters D and d, the values of the mean dia. $\bar{d}$ and the annular gap G are determined using the three linear scales at the right as follows:

First, using the right-hand sides of these scales, note the value of the mean diameter $\bar{d} = \frac{D+d}{2}$ using the scales marked $D+$ and $+d$.

Next, using the left-hand sides of these scales, note the value of the gap $G = \frac{D-d}{2}$ using the scales $D-$ and $-d$.

This value of G is transferred to the adjacent logarithmic scale. Then, as illustrated in the example, go through the value of $\bar{d}$ previously noted to the first reference line and then through the values of L, H, ν to find the volume flow, Q_o.

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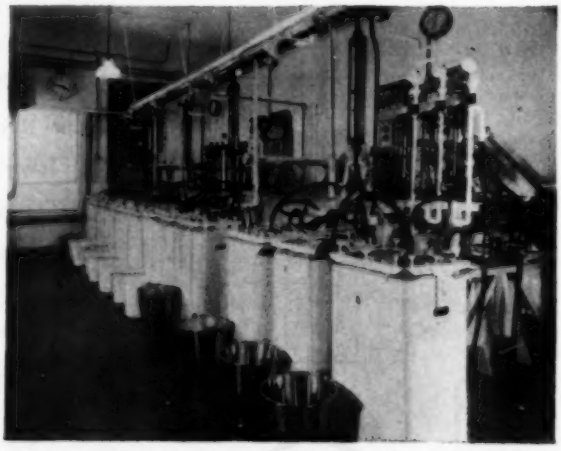
Washing Machines as Laboratory Fermenters

by A. Borrow, E. G. Jefferys and I. S. Nixon

As laboratory fermenters for the study of mould metabolism, 30-l. stainless-steel washing machines (Hoover Ltd's., Model 0307) have been in use at the Akers Research Laboratories of Imperial Chemical Industries Ltd., Welwyn, Herts., for the past six years. The assembly is inexpensive—for a single machine complete with modifications and ancillary equipment costs only about £100—it is easily handled, and has not deteriorated in continual use.

To convert a washing machine into a fermenter, the wringer is removed and the rivet holes filled with stainless-steel rivets. The lid is replaced by a flat stainless-steel plate which carries an internally-baffled stainless-steel heat-exchange pad in contact with the fermentation medium. Water at a constant temperature is pumped through this pad. Three holes are provided in the lid—two, for sampling and for adding medium, are closed with rubber bungs, and the third, for discharge of air and foam, is fitted with a rubber bung carrying a wide-bore glass bend. A synthetic rubber washer is placed between the lid and the tub, which are clamped together.

The fermenter, with the motor removed, may be sterilised separately from the medium, which is later siphoned into the tub. This procedure is followed for fermentations in which the *p*H remains below 4.5, when contaminating bacterial growth is rare, but for fermentations at a higher *p*H it is more reliable to sterilise the medium in the tub, which is then replaced in the frame of the machine. The fermenter is connected to a supply of humidified and sterilised air through the original drain hole at the bottom of the tub, the motor is fitted and agitation is provided by the circular ribbed pulsator of the washing machine. Samples for analysis are removed with sterile pipettes through one of the holes in the lid. The liquid level should not be allowed to fall to a point where the efficiency of the agitator decreases.



Converted domestic washing machines in use as pilot fermenters at Akers Research laboratories.

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PROCESS ENGINEER'S NOTEBOOK

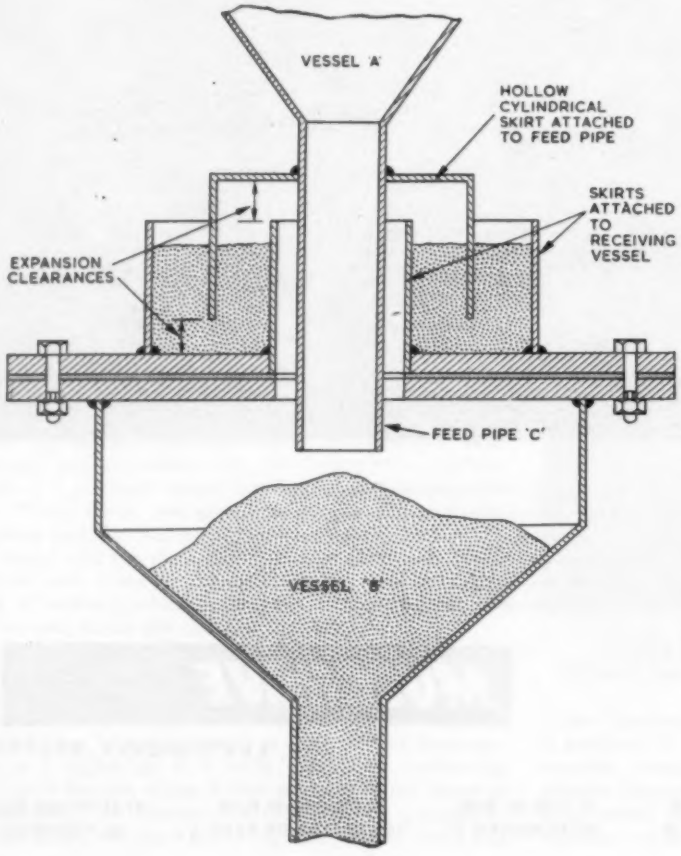
Simple Expansion Device for Hot Pilot Plant

THERMAL EXPANSION caused by large temperature changes in process plant usually necessitates the incorporation of expensive expansion joints.

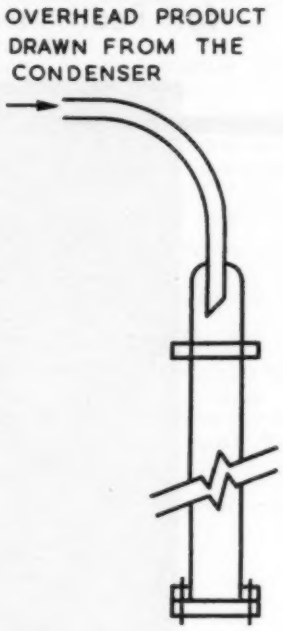
The diagram shows a simple device which has been used successfully for several years in a pilot plant handling granular solids at rapidly changing temperatures in the range 300-800°C. The solid passes from vessel (*A*) to vessel (*B*), through a feed pipe (*C*) which is not connected to vessel (*B*). A seal is obtained by means of the skirt system illustrated. Two concentric metal pipes are welded to the lid of (*B*); the inner pipe being of equal diameter to the hole through the lid. The annular space so formed is filled with fine granular material, e.g., sand. A skirt attached to the feed pipe (*C*) dips into the granular material. The depth of granular material required can be calculated from a knowledge of internal pressure. Clearance distances (see diagram) can be calculated knowing the expansion properties of the material of construction. Rigid supports can be attached to the vessel.

This system has been used successfully in standpipes of pneumatic transport systems and between cyclones and receiving bunkers.

W. H. NEWTON



Fraction Collector for Pilot-plant Vacuum Distillation



IN DISTILLING HIGH-MELTING liquid, say in the melting point range 25-70°C, the fact that the material may solidify in the pipes and valves if these are not properly heated may lead to serious interruptions of the process. In vacuum systems restriction of pipes by solidified matter is highly undesirable. The following method for fractionating fatty acids by batch distillation in pilot plant has proved satisfactory for small quantities.

The overhead product is withdrawn from the condenser in the liquid state to the product receiver. This is a vertically mounted glass tube with a cross-section 1-2 in. and length according to the volume of the product. The bottom end is closed by a blind flange.

The first impure fractions of the product fall to the bottom of the tube and solidify. The purer products solidify in layers up the tube. When the distillation is finished, the tube is taken down and the pure product is easily separated from the impure by partial melting or by scraping out the solid.

Simple Entrainment Separator

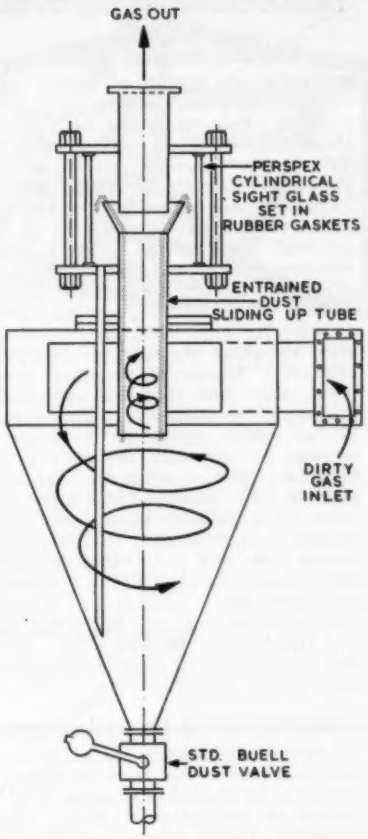
IT HAS BEEN frequently noted both in the literature and in practice that the efficiency of separation of liquid/solid, liquid/gas and solid/gas cyclones is considerably reduced by the entrainment of the dispersed separating phase by the continuous phase. Some evidence points to the existence of a stationary annular layer surrounding the outlet pipe or vortex finder and it is possible that particles are entrained at the entrance to the outlet pipe by the contra-rotating vortex of the outgoing continuous phase.

Some attempts have been made to prevent this by the fitting of a skirt around the entrance, but this method is of very limited application. The sketch indicates a simple method that has been tried in practice and which can be observed working and performing the required disentrainment. This consists of splitting the outlet pipe just above the cyclone and introducing a conical enlarging section in this discontinuity in the pipe.

The contra-rotating vortex of the continuous phase throws the entrained material against the wall, giving it both a radial and vertical velocity. The vertical velocity is, however, insufficient to bridge the discontinuity introduced in the path and the solid or liquid dispersed phase follows the cone to be deposited in the perspex collector pot immediately the imparted vertical velocity has been lost. The down pipe draws down the deposited material into the main body of the separated stream by reason of the pressure differential introduced by the tangential velocity of the main stream across the outlet of this down pipe. This can be clearly seen through the perspex sight glass.

The diagram (right) illustrates how an existing cyclone was modified by the addition of the "look box". The down pipe, through which the separated entrained material is returned to the main body of fluid in the cyclone, is attached to the lower plate of the cylindrical box.

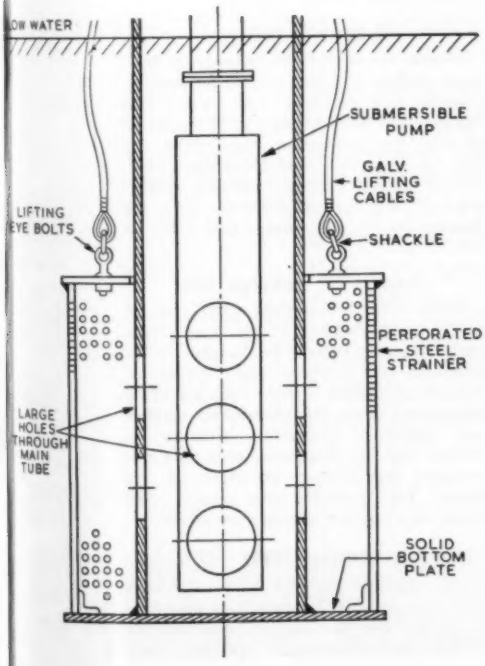
F.W.M.


GAS OUT
PERSPEX CYLINDRICAL SIGHT GLASS SET IN RUBBER GASKETS
ENTRAINED DUST SLIDING UP TUBE
DIRTY GAS INLET
STD. BUELL DUST VALVE

Strainer for Submersible Pump Operating on River Water

THE SUCTION PIPES of all large submersible pumps handling river water are fitted with perforated metal strainers which must be below the low water springs level and thus cannot be cleaned without raising. Some installations have a hinged joint which usually rusts up until immovable, but usually to clean the strainer entails the removal of the pump, together with the bottom length of pipe and strainer. The sketch shows a type of strainer used by the author and which worked well on really filthy Thames water. The submersible pump is within a large bore tube for protection against mechanical damage and/or dropping in the river. This tube has a blank plate of larger diameter welded to the bottom. The strainer, a cylinder of perforated steel, has an annular steel ring welded at the top; this to be a loose fit over the tube containing the pump. When the strainer is known to require cleaning, the pump is shut down and the strainer hauled above the water level for cleaning by means of the galvanised cables which are left permanently attached. This is a comparatively quick and easy operation and may be carried out with any light chain block. The operation is normally, of course, carried out at low water.

R. H. B. MATTHEWS



Contributions invited

THE EDITOR invites readers to submit, for possible publication in "Process Engineer's Notebook", notes on practical devices that have been elaborated on the job for improving the operation or increasing the safety of processes, or that have been extemporised in special circumstances. The contributions preferably should be of about 250-500 words, and be illustrated with a line diagram or sketch, or a photograph. A minimum of three guineas will be paid for each contribution used. They will be published anonymously or under the contributor's name, according to his wishes.

World of Chemicals

Brazilian Chemical Imports

Brazil's total imports of organic and inorganic chemicals between 1955 and 1957 have been running at the rate of about U.S.$60,000,000 per year, according to a report prepared recently by the Commercial Department of the British Embassy in Rio de Janeiro. The character of the market is, however, one of continual flux, because of the rapid development of new industries and the growth of indigenous chemical manufacture; the former creating new demands for importation and the latter often abolishing overnight the need for substantial imports of important products. Apart from medicinal and pharmaceutical preparations, some 450 separate items appear in the import statistics for chemicals, but there were only sixty items of which the total imports in 1957 exceeded U.S.$100,000 in value. These included caustic soda (1957 imports U.S.$9,099,293); sodium carbonate (soda ash) (U.S.$4,638,320); carbon black (U.S.$3,270,236); styrene (U.S.$2,023,384); titanium dioxide (U.S.$1,549,307); dioctyl phthalate (U.S.$1,402,844); sulphonamides and their derivatives (U.S.$1,258,765); and ureas (U.S.$1,183,767).

Berre Petrochemicals Development

A new complex of chemical plants has been brought into operation by Société Anonyme des Produits Chimiques Saint-Gobain at their plant at Berre, near Marseilles, France, adjacent to the oil refinery of Compagnie de Raffinage Shell-Berre. The new facilities will enable Shell Saint-Gobain, in which the Royal Dutch-Shell group of companies has a 60% interest, to manufacture Epikote resins and base materials for carbon black, detergents and also to expand their range of organic solvents. At Berre, also, Société des Elastomères de Synthèses, a joint company formed by Shell Saint-Gobain, Texas Butadiene & Chemical Corp. (an associate of Godfrey L. Cabot, Boston), Michelin, Kleber Colombes and Dunlop are erecting a plant for the manufacture of 50,000 tons per annum of styrene-butadiene synthetic rubber, and this is expected to begin production in 1961.

Japanese Nuclear Power Station

A design for Japan's first nuclear power station at Tokai Mura, 65 miles north-east of Tokyo, submitted by The General Electric Co. Ltd. of England in collaboration with Simon-Carves Ltd., has been approved by the Japan Atomic Power Co. and will form the basis for the negotiations of a contract. The negotiators hope that the details of the contract, the total value of which will be about £30 million, will be finalised later this year, and in this event G.E.C., as the main contractor, will be responsible for the design of the entire project. Certain items, however, will be manufactured by Japanese firms working to the Group's designs. The power station, which will have a net electrical output of 150,000 kW, will be powered by a single gas-cooled graphite-moderated reactor of the same basic type as the two reactors at present being built by the Group at Hunterston in Scotland. Novel features have been embodied in the design of the structure and controls to ensure the safety of the installation under earthquake conditions.

Australian Oil Search

By the end of 1959 more than £A20 million of overseas capital will have been invested in the search for oil in Australia and Australian territory. It is coming from sterling and dollar sources and it includes more than £A12 million spent since 1956 on oil exploration in Papua-New Guinea. More than £A6 million will have been invested in Western Australia and £A1 million in South Australia.

Finnish Titanium Oxide Plant

The State-owned company, Vuorikemia Oy, is to erect a titanium-oxide plant at Pori with a capacity of 16,000 tons a year. The plant is expected to be operating in about two years' time, and orders for over half of the machinery needed have already been placed in Finland. A new sulphuric acid plant to supply raw material to the titanium-oxide works will commence operations in 1960. The building is ready (at Hargavalta), but installation work will not be completed this year.

Nuclear Beryllium Products

Imperial Smelting Corp., the U.K. operating subsidiary of Consolidated Zinc Corp. is installing plant at Avonmouth which will be the first commercial production unit for nuclear-grade virgin beryllium metal in the U.K.

W. European Petrochemicals Production

West Europe's output of petrochemical products rose by 30% to 830,000 tons in 1958, according to a Deutsche Shell report. By the end of 1960 it is expected to reach an annual rate of nearly 2 million tons, and large enough to satisfy most of West Europe's demands. Leading producers last year were Britain, with 327,000 tons, West Germany with 187,000 tons, France with 142,000 tons, Italy with 130,000 tons, and the Netherlands with 45,000 tons.

Southern Rhodesian Lime and Fertiliser

A new £150,000 factory which has been designed to produce twelve varieties of fertilisers is being built in Salisbury by Windmill Fertilizers Rhodesia (Pvt.) Ltd. The factory will have a capacity of at least 50,000 tons of fertiliser annually. An extensive reconstruction programme is to be undertaken by Northern Rhodesia Lime Co. Ltd near Ndola. The project, which will cost about £500,000, includes a modern factory and expansion of quarrying activities.

Soviet Science Plans

Priority has been given in the mapped out seven-year plan for Soviet science by Professor Nesmeyanov, the president of the U.S.S.R. Academy of Sciences, to the problem of harnessing the power of nuclear fusion for electricity generation. Control of the thermo-nuclear reaction is, however, admitted to be a long-term task. Other projects include the transformation of fuel directly into electric power; obtaining metal directly from ore and the creation of materials with properties made to order.

Pernis Acid Plant

Albatros Superfosfaatfabrieken n.v. of Utrecht is founding a new company in which Cyprus Mines Corporation of Los Angeles will participate. The company is to erect at Pernis, near Rotterdam, a sulphuric acid plant described as one of the largest and best equipped in Europe, and it will produce and market chemical products. As raw material for acid manufacture, C.M.C's flotation pyrites will be used.

Carbon Brick Plant Commissioned

Initial shipments totalling nearly 700,000 lb. of a new grade of carbon brick for blast furnace linings have been made from Union Carbide's new plant at Lawrenceburg, Tenn., claimed to be the most highly automated plant for the production of carbon products in the U.S.A. The plant simultaneously forms and bakes carbon products, reducing processing time from as long as eight weeks to less than eight minutes.

Belgian Industry

Production in the oil industry in Belgium during 1958 was greater on average than in the previous year (index 205 against 169), but during the two months of the year production was below the rate for November and December, 1957. Output of nitrogenous fertilisers, typifying that of chemicals generally, rose, the indexes for the two years being 140 and 146.

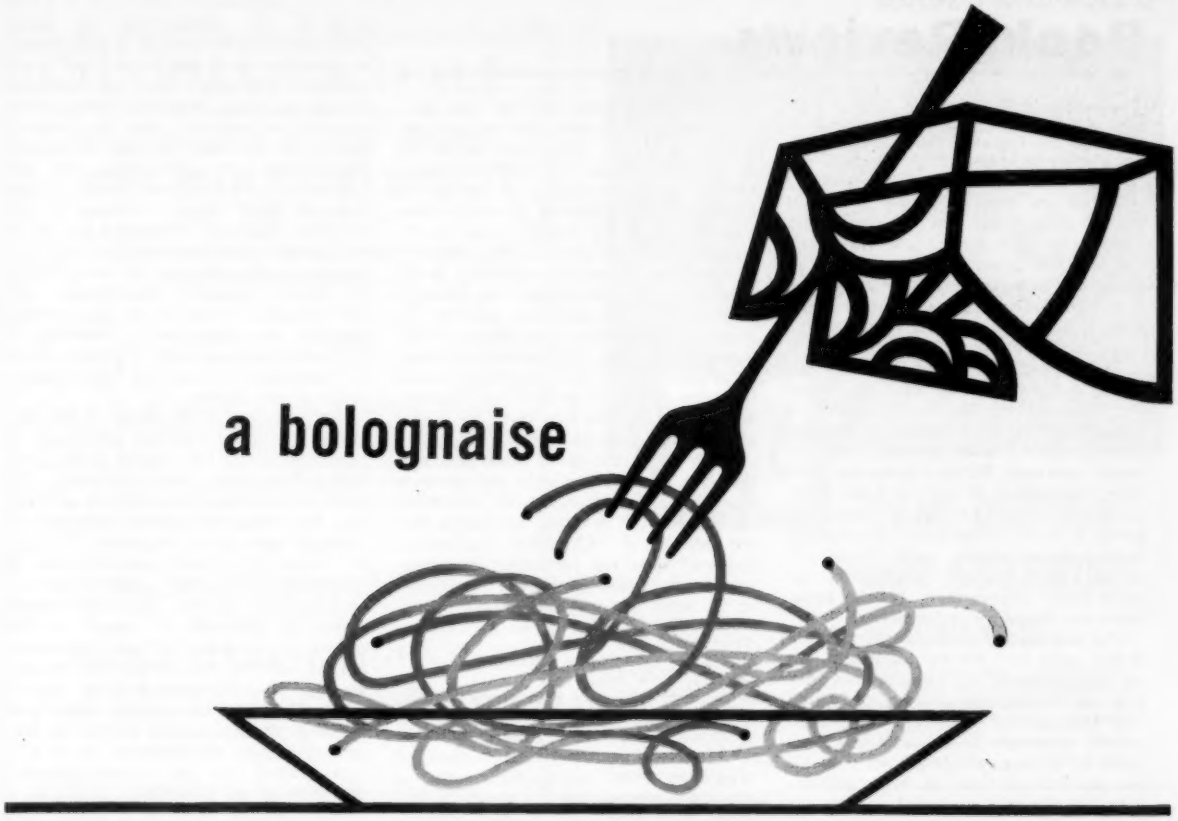
Changes in Embargo List

Items recently removed from the list of goods embargoed to the Soviet bloc and China are mainly in the groups for scientific instruments and apparatus, servo-mechanisms and photographic equipment, and for chemicals, plastics and synthetic rubbers. Mercury is deleted and the fissionable materials embargoed are further qualified. In the group for miscellaneous goods and machinery nuclear reactors are added.

Achema, 1961

The ACHEMA 1961 13th exhibition and congress of chemical engineering organised by the DECHEMA will be held in Frankfurt from June 9-17, 1961.

BCE 5271 for further information



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Book Reviews

Vapour-liquid Equilibrium

by E. Hala, J. Pick, V. Fried and O. Vilim* Translated into English by Dr. G. Standart. Pergamon Press, London, 1958, 402 pp., 90s.

THIS is a valuable book presenting a full and consistent development of the fundamentals of vapour-liquid equilibrium. It is divided into three parts entitled The Thermodynamics of Solutions of Non-electrolytes (143 pages), Laboratory Technique (150 pages) and Vapour-liquid Equilibrium Data (66 pages) and contains 1232 references.

Solutions of the Gibbs-Duhem equation based on the work of Carlson and Colburn and of Wohl are given for binary and ternary mixtures. Redlich and Kister and other equations are also briefly surveyed. Worked examples illustrate applications of the van Laar, Margules, Redlich and Kister equations giving a direct comparison of observed vapour compositions with those calculated from activity coefficients for given liquid compositions. Ternary equations are classified and surveyed.

The second part gives details of equilibrium stills and survey techniques for the measurement of pressure, temperature, vapour pressure and boiling points. The treatment is good and well illustrated, although it is surprising that heats of mixing, which are so valuable for the interpretation of many isobaric data, are virtually neglected.

In the third part equilibrium data are presented, although no attempt has been made to assess the accuracy or consistency of these data.

This book will undoubtedly prove useful to industry in presenting an overall picture of equilibrium data, their tabulation, determination and correlation.

S. R. M. ELLIS

**Department of Physical Chemistry, Institute of Chemical Technology, Prague, Czechoslovakia.*

Chemical Engineering Practice, Volume 6

by Cremer and Davies Butterworth's Scientific Publications, London, 1958, 600 pp., 95s.

THE volume is called Fluid Systems II and is the sixth of twelve under the general editorship of Cremer and Davies or Watkins. It includes fifteen articles on the following eleven subjects: packed towers; evaporation; fluidisation; gas liquefaction; refrigeration; leaching; crystallisation; colloids; filtration; centrifuging; and sublimation. Each subject is derived from its first principles and there is an extensive European bibliography. Consequently, although there is rarely sufficient knowledge to link theory and practice without factors of safety, the persistent inquirer will be able to appreciate their importance. The services of experts in their respective fields have been attracted by the editors who have drawn about equally from industry and the universities. This resembles the procedure adopted by Perry in editing the "Chemical Engineer's Handbook", which is probably the most widely used of all treatments of the subject, four editions having been published in America since 1933.

It would be expected that two sets of contributors using the same sources and following similar objectives would be unlikely to prepare very different treatments: it was therefore of interest to compare Fluid Systems II with those sections of Perry which most nearly covered the same ground. The comparison has shown that the treatments in the present volume are similar to those in Perry rather than markedly superior. In some instances there are minor advantages; for instance, the treatment of matter transfer is not handicapped by over-insistence on the Transfer Unit Concept. Nevertheless, there has been no major advance on a broad front.

Since no profusion of fresh information has become available and no new ideas have been injected for presenting the old facts, it is hardly surprising that the editors of "Chemical Engineering Practice" have not succeeded in surpassing results achieved by the Americans in 25 years of sustained effort.

W. F. CAREY

Gas Chromatography, 1958

Edited by D. H. Desty Butterworth's Scientific Publications, London, 1958, 383 pp., 70s.

MOST chemical engineers will be aware of an analytical method of separating the components of a vaporised mixture using a specially prepared column packing to effect differential absorption or adsorption, and which is now termed gas chromatography. The possibilities of the process as applied to the physical separation of vaporised mixtures on a technical scale may not be so well known. This book describes in detail apparatus that has been used for both analytical and "preparative-scale" separations.

The proceedings of a symposium held in London in 1956 were embodied in a book entitled "Vapour Phase Chromatography". The book now under review records the proceedings of the second symposium held during May, 1958, in Amsterdam, under the joint auspices of the Hydrocarbon Research Group of the Institute of Petroleum and the Royal Dutch Chemical Society.

The contents of the book are divided into three main sections bearing the subtitles theory, techniques and apparatus, and applications, respectively. Each section comprises nine or ten papers, making 28 papers in all. The discussions that followed the presentation of the papers are fully recorded and in several instances provide further information of value regarding the subject-matter, as well as helping to elucidate questions that arose out of the papers.

The subjects dealt with under the heading of theory include "column efficiency" and its relation to the operating behaviour of different kinds of column packing. Some effects that are dependent on adsorption and solute-solvent interaction are also examined. The papers that deal with techniques and apparatus include descriptions of various types of detector, the construction of high-efficiency columns capable of separations at pressures up to 200 lb./in.^{2}, and comparative operating data on different stationary phase supports, temperature variation of column, base line control, carrier gas flow rate and size of sample. Descriptions of applications of gas chromatography include several items that are likely to be of interest to the chemical engineer. Particulars are given of a larger-scale apparatus arranged for the automatic collection of a succession of purified samples. Descriptions are also provided of the use of gas chromatography in plant control, including a particular application to determine traces of hydrogen in water of high-pressure steam power plants.

Although the book under review discloses useful information additional to that contained in the records of the 1956 Symposium, there are, inevitably, instances where the same kind of problem that has been investigated previously is repeated with minor variations. It is unfortunate that a finally agreed system of nomenclature does not appear, even yet, to have been reached. There still remain points of difference in regard to the theory of operation of gas chromatography and the most useful way of presenting the data gained from experiment. The chemical engineer will regret the absence of a concise method of presenting column performance. As at present defined for gas chromatography, the number of theoretical plates in a column applies only to a single substance and does not indicate the degree of separation that may be achieved in practice between two or more substances, a condition that the engineer may find perplexing. It is satisfactory to know that the discussions that are now taking place between the people intimately concerned with the process are intended to resolve such anomalies.

The book as a whole should prove a useful work of reference to those practising in the field, and to all who wish to have an up-to-date summary of the present state of development of gas chromatography. The appearance of the book so soon after the presentation of the papers reflects great credit on the editor, his associates and the publishers, who deserve the highest praise for reproducing the papers, discussions and diagrams in such an attractive format.

G. BURROWS

Fast Reactions in Solids

by F. P. Bowden and A. D. Yoffe Butterworths Scientific Publications, London, 1958, 164 pp., 40s.

THE development and propagation of explosions in solids bears a number of resemblances to related, but perhaps simpler, phenomena in gases. Thus we have rather similar concepts of minimum ignition energy, induction period. burning velocity and high-speed detonation. The well-developed techniques of chemical kinetics, which are so helpful in the quantitative understanding of the development of explosions in gases, cannot, however, be applied so readily to solids. We do not have such simple variables as mixture strength, gas pres-

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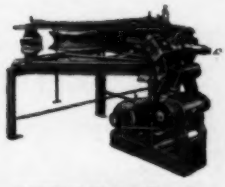

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Book Reviews continued

sure and vessel dimensions; instead, such factors as crystal size, presence of occluded gas bubbles and crystal strain due to impurities become important. The inherent difficulties are thus considerable, but the use of modern refined techniques, such as those of high-speed photography and fast electronic methods, combined with high resolution electron microscopy and electron diffraction, have enabled remarkable progress to be made.

This book is in no sense a revision of the authors' earlier "The Initiation and Growth of Explosions in Liquids and Solids", but is supplementary to it, covering the many recent developments. Chapters deal with the slow decomposition of crystals, thermal explosions, structure and stability of inorganic compounds, initiation of explosion by shock, initiation of explosion by light, decomposition and ignition by nuclear particles and ionising radiations, spontaneous explosions, and fast growth of explosion.

Apart from a short theoretical section in the section on thermal explosions, the approach is entirely experimental. A large amount of work on the initiation of explosions is reviewed; the initiating causes include heat, impact, friction, light, electrostatic discharges, fast electrons, slow neutrons, α-particles, X-rays and γ-rays, and the variables, besides temperature, include crystal size, pressure, and the presence of gas occlusions and sensitisers. This detailed work on numerous explosives, involving reference to around three hundred recent papers is not particularly easy for continuous reading, but it will be most valuable for the serious worker in the field to have these data summarised so concisely.

Ignition generally is believed to be thermal, with special ionising or chemical effects sometimes preceding the heat release which leads to continued propagation. The transition from slow burning, through the incompletely understood slow detonation, to high-speed detonation is discussed. The stability of types of compounds is examined, and it is shown that ionic-type crystals tend to be more stable than the covalent type.

The book is well produced, illustrated with many excellent photographs and supplemented with several appendices of data. This work, by two established authorities. Drs. Bowden and Yoffe, who have contributed so much to the field, may be recommended whole-heartedly.

A. G. GAYDON

Progress in Non-destructive Testing, Volume I.

Edited by E. G. Stanford and J. B. Fearon
Heywood & Co. Ltd., London, 1958, 268 pp., 60s.

ONE of the editors of this book is vice-chairman of the Non-destructive Testing Group of the Institute of Physics, and the policy of that Group, during recent years, has been heavily to emphasise the basic physics both of accepted methods of non-destructive testing and of techniques possibly capable of development into testing techniques. The present volume is based upon the same outlook, and some of the material in it has previously been presented before that Group. Each of the eight contributions is by an authority in his field, while the content ranges from a reappraisal of the technique of fluoroscopy in industrial radiography as modified by such recent developments as ultrafine focus X-ray tubes and image intensifier systems to a description of the application of nuclear magnetic resonance. These resonances may be detected using radio frequencies in the range 1-40 Mc/s and magnetic fields of the order of 10 kilogauss. Of the range of stable nuclei, some 130 are, in principle, detectable, and applications proposed include crystal structure determination, the detection and measurement of liquid impurities in solid materials (e.g., moisture in grain and other agricultural products) and polymer investigation. The resonances are shifted by ionic bonds, and may be affected by impurities in the sample, thus enabling some chemical analyses to be made; also, information may sometimes be obtained on alloy systems.

In other articles the propagation of ultrasonic waves in solid media is described, with particular reference to the factors leading to difficulty in correlating the flaw echo amplitude obtained in test methods with the size of the flaw, owing to diffraction and other effects, and a survey is made of electromagnetic test methods. These can be made very versatile; they are capable of sorting different alloys or different heat treatment conditions of an alloy, and of detecting discontinuities and internal stresses. Many of the practical difficulties in applying the methods arise in suppressing indications arising from variables not of interest. A newer technique is the measurement of the damping capacity of materials, which can give information on internal stress, grain boundary slip and lattice dislocations in metals and also the onset of fatigue. Visco-elastic processes in polymers, and the solid-liquid transition can also be studied, and there are particular applications to semiconductors, ferrites, ferroelectrics and ferromagnetics, and glass-like materials.

In another article the use of thermal conductivity measurements is described, both on materials of low conductivity such as building materials and the earth's crust (as, for instance, when laying power cables), and for measuring plating thickness, sorting alloys and so on. A very simple thermal comparator is proposed which nevertheless enables sufficiently accurate measurements of thermal conductivity to be made on materials within the entire range from copper to plastics and expanded insulating material. Other articles deal with neutron radiography and some techniques employed in medical research

P. L. DEGAN

SHORTER NOTICES

The Pump Users' Handbook

Compiled on behalf of the British Pump Manufacturers' Association by Herbert Addison, O.B.E., M.Sc., M.I.C.E., M.I.Mech.E.
Pitman, London, 1958, 122 pp., 30s.

THIS HANDBOOK has been sponsored by members of the British Pump Manufacturers' Association with the aim of offering direct help and guidance to owners and users of pumping plant. It includes practical discussion of installation, maintenance, diagnosis of troubles and pump testing. There is a table indicating the range of discharge and head for pump types, and one giving suggestions for types of pump for various liquids. Finally, there is a table of pumps supplied by members of the Association. There is no reference to metering pumps.

Fertilisers — Production, Consumption, Prices and Trade in Europe

O.E.E.C., Paris, 7th Study 1955-1953, 8 4, 7s

THIS REPORT is based on information received from member countries of the O.E.E.C. and Spain in reply to a questionnaire identical with that used by the Food and Agriculture Organisation of the United Nations. It includes an analysis of the situation for nitrogenous fertilisers, phosphate fertilisers, potash fertilisers and agricultural lime, together with statistical appendices.

Water Economy in Iron and Steel Works

O.E.E.C., Paris, 1958, 72pp., 8s.

A GROUP of six experts from four countries visited German, French, Italian and Austrian iron and steel works to examine problems of water economy. This report gives details of the observations in each case, together with a survey of legislation and regulations in the countries visited. Apart from many detailed observations, the single general recommendation is that special attention should be paid to re-cycling water, since it is evident that a closed-circuit system requires much less water than other systems.

British Standards

Steel Pipe Flanges and Flanged Fittings (Nominal sizes ½ in. to 24 in.) for the Petroleum Industry. B.S. 1560:1958. B.S.I., London, 25s.

THIS BRITISH STANDARD is one of a series prepared under the authority of the Petroleum Equipment Industry Standards Committee. It was first published in 1949 when, in view of the international character of the petroleum industry, careful consideration was given to American Standard ASA.B16.e, "Steel pipe flanges and flanged fittings", in order to ensure interchangeability in practice between flanges and flanged fittings produced by American and British manufacturers. The present edition of B.S. 1560 has therefore been aligned with the provisions of the latest edition of the American Standard and all dimensions in the former correspond to those in the latter, except for slight variations in the wall thicknesses of fittings. This standard now applies both to ferritic steel and austenitic stainless-steel flanges and flanged fittings. It is intended to include metric equivalents in the next revision.

Under pressure, we'll admit...

... there's quite a lot we know about the behaviour of pipes. Teddington Bellows Expansion Joints are designed and engineered to take up and absorb expansion, contraction and lateral movement of piping in a wide variety of industries.

After Teddington Bellows have been butt-welded from highly finished cold rolled stainless steel sheets, convolutions are introduced to give the bellows their characteristic flexibility under pressure.

Nuclear, chemical, marine and gas engineers acknowledge their efficiency and superiority over many older forms of expansion joints.

Wherever pipe-work is subjected to vibration or movement in any direction, a Teddington Bellows with a suitable end-fitting will solve the problem.

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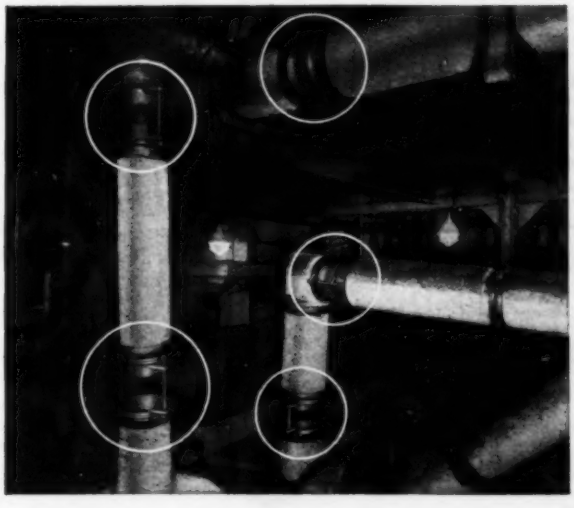
Teddington Bellows are produced in technical collaboration with the Solar Aircraft Co., U.S.A.



pipes on the move prefer

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EXPANSION JOINTS

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Ammanford, Carmarthenshire. Tel: Ammanford 2255

PLANT EQUIPMENT NEWS

Glass-lined Vessels

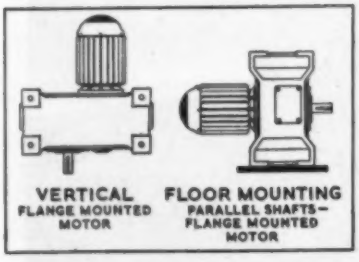
Acid - resistant, glass-lined, steel evaporating pans, open and closed jacketed tanks, receivers, reaction kettles, storage tanks, heat exchangers and stuffing boxes made by Schwelmer Eisenwerk are being handled in Britain by QVF. Capacities of vessels vary in most cases from 40-8000 litres. The announcement states that the equipment is highly resistant to chemical attack, extreme temperatures, temperature shock, pressure and vacuum. The non-porous glass enamel coating used in the tanks and vessels consists of several layers and may be exposed to temperatures of up to 250°C or down to −50°C. As a result of the hardness and elasticity of the coating, it is resistant to abrasion and particles do not adhere to it, which facilitates cleaning. **QVF Ltd., Fenton, Stoke-on-Trent.**

BCE 5331 for further information

New Types of Reduction Gear

A wide variety of mounting positions, shaft dispositions and speed reduction ratios are the principal features of two new types of worm reduction and helical gear units now being manufactured by Crofts. In the case of the worm gears, adaptability is secured by means of a standardised case cast with integral feet. In that of the worm reduction gear unit, which can be supplied in motorised form if desired, up to 50 mounting positions and arrangements of input and output shafts are possible. The design permits ready change from one assembly to another without causing excessive stripping or fitting and a right- or left-hand assembly is easily effected. The horsepower range of the gears at present available is from fractional to 50 h.p. and stock gear ratios vary from 5 : 1 to 70 : 1. The helical gear is similarly adaptable and will give a wide range of ratios and can be supplied with input and output shafts either parallel or at right angles. The unit can be supplied for transmitting horse-powers as high as 500. A unique feature of this design is that, regardless of the size or combination of gears, the input and output shafts are in the same horizontal plane, and for each size unit are dimensionally in the same disposition to each other, whether utilising single, double or triple reduction gear trains, or arranged as parallel shaft units or as right-angle drives. **Crofts (Engineers) Ltd., Bradford, 3, Yorks.**

BCE 5332 for further information



Small Vacuum Pumps

Details have been received of a range of small high-vacuum pumps suitable for use in the small-scale pilot plant and laboratory. The Genevac single-stage high-vacuum rotary piston pumps are obtainable in 2, 4, 8 and 12 cu. ft per min. capacities with an ultimate vacuum of less than 0.005 mm Hg. The double-stage models have capacities of 2, 4 and 6 cu. ft per min. and are capable of an ultimate vacuum of less than 0.0002 mm Hg. The design permits of higher pumping speeds at 100 microns and the pressure rise is less than 0.5 mm Hg. with maximum ballast. The necessity for oil changes is reduced to a minimum due to the oil circulation filter system. **Genevac Ltd., Radcliffe, Lancs.**

BCE 5333 for further information

Exhaust Fans

John Bass announce that in the Bassaire range of extraction fans both centrifugal and axial-flow principles are used. Fabricated unplasticed PVC is employed in their construction and fume condensate traps are fitted. The motor and the PVC impeller may be withdrawn as one unit for ease of inspection. The range is available in horizontal models, or, for use on fume cabinets, in vertical models. **John Bass Ltd., 36 The Broadway, Crawley, Sussex.**

BCE 5334 for further information

Electrically-powered Actuator

An electro-mechanical screw jack which can be stopped at any desired position instantly, and will hold the load indefinitely at this setting, has recently been announced by Teleflex Products Ltd. This actuator can be operated manually in the event of a mains failure. Power output can be set to any predetermined value and may be varied between 40 and 4000 lb. The standard stroke is 12 in. and ram speed 16 or 32 in. per minute. An overload trip is fitted which can automatically stop the actuator and switch off the electrical supply, thereby completely safeguarding the mechanism against excess loads.

Adjustable cam-operated limit-switches limit travel in either direction. They are fully enclosed and visual indication of direction of travel is given through a window. A standard fitting is a twin disc brake, electrically released, to check over-run and provide instant and positive locking at any position of the stroke.

Applications of the actuators include operation of groups of valves from a centre control panel, operation of valves or dampers which are normally inaccessible, remote control of equipment in areas which are dangerous to life; for example, in chemical and nuclear engineering. Signals of movements are relayed to the instrument panel without additional outside linkages. Price is £150. During a recent Press visit to the factory, a model of this actuator was seen on life test. It had then completed over three-quarters of a million cycles. **Teleflex Products Ltd., Basildon, Essex.**

BCE 5335 for further information

New Crusher

A crusher capable of producing, for example, agricultural lime, at the rate of 10 tons an hour is being made available by **The Patent Lightning Crusher Co. Ltd., 14a Rosebery Avenue, London, E.C.1.**

BCE 5336 for further information

Pressure Couplings

Exactor are in course of developing a self-sealing coupling for use with a variety of fluids, which can be under pressure in either or both halves simultaneously. It will enable, for example, a pipeline to be connected into, or disconnected from, a pressurised vessel simply by turning the hose half of the coupling. **Exactor Works, Church Way, Edgware, Middx.**

BCE 5337 for further information

Polythene Bins

50-gallon polythene bins, made with or without a pouring lip, are the latest addition to the range of containers now being made in Britain by the Engel process. They are available in rigid or flexible polythene, and specially designed steel holders are supplied where the bins are to be moved or tilted when full. The holders are cadmium plated, but may be chromium plated or supplied in stainless steel if required. White Child &

DV-2 Centrifuge

We cover the whole range!

Sharples make every type of disc centrifuge . . .

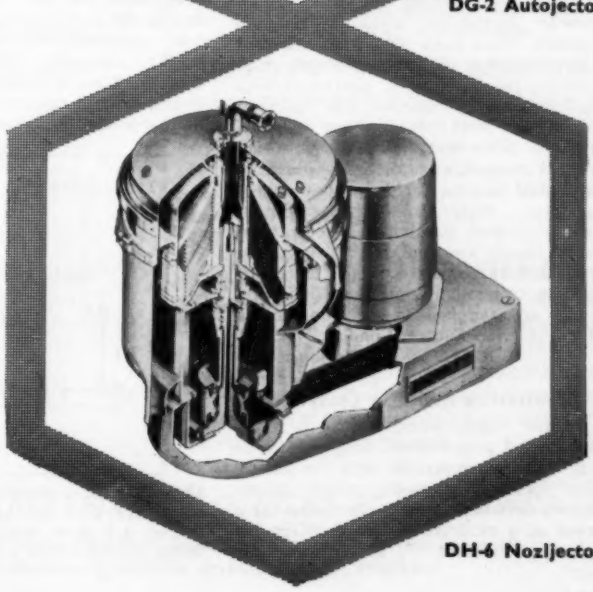
Only Sharples can offer a centrifuge for every problem including a complete range of disc centrifuges, three of which are the Controlled Solids Discharge DV-2 Centrifuge, the DG-2 Autojector and the DH-6 Nozljector.

Controlled Solids Discharge DV-2 Centrifuge discharges solids from the bowl continuously by means of valves which are controlled by an external timer. Instantly variable control of solids discharge is thus at the operator's fingertips.

The DG-2 Autojector. In this case build up of solids in the bowl automatically opens the valves, which allows the DG-2 to handle variable feed material. Consistent operation without attention is ensured by this unique design.

The DH-6 Nozljector has the largest capacity of the Sharples range of nozzle discharge disc centrifuges. In fact it has a higher capacity than any other machine of this type in the world.

DG-2 Autojector



DH-6 Nozljector

SHARPLES

SHARPLES CENTRIFUGES LTD. · TOWER WORKS
DOMAN RD. · CAMBERLEY · SURREY · *Camberley 2601*

PLANT EQUIPMENT NEWS

Beney's range of containers now includes straight-sided and round units with and without lids from 6- to 50-gal. capacity. **White Child & Beney Ltd., Shepley Works, Audenshaw, near Manchester.**

BCE 5338 for further information

Vibrationary Ball Mills

Apex Construction have extended their range of vibratory ball mills, and 10 mills with capacities varying from 0.5 to 250 litres can now be supplied. Vibratory mill No. 163, for example, employs a new principle by which the mill, instead of causing the balls to cascade through rotation of the mill, produces the grinding action through high-frequency vibration which causes the balls to reduce the material by impact and by a rotary movement. This action produces particles in the micron and sub-micron sizes. Moreover, the particle size reduction is accomplished more rapidly and many materials which could not be reduced to particle sizes of the above magnitude by conventional ball mills can now be disintegrated to this extent. The particles produced are very uniform in size and through the absence of excessive quantities of fine material there is a great saving in power. As a result, classification of the product during grinding is not necessary, since the spread of particle sizes is very small. These mills have already been used for grinding and mixing the products of powder metallurgy, including tungsten carbide. They have also been used for the production of fine graphite for lead pencils, paint pigments, pharmaceuticals and many other materials. The bodies of the larger sizes of vibratory mill are troughs fitted with lids. They are supported on springs and driven by means of an out-of-balance mechanism powered by an electric motor. In the larger sizes of mill, mild-steel, stainless-steel and rubber-lined vessels are available which can be provided with water cooling if necessary and porcelain or non-corrodible steel balls are supplied. **Apex Construction Ltd., 15 Soho Square, London, W.1.**

BCE 5339 for further information

Centre-line Indicator Controller

Either simple on-off control or time-modulated proportional control may be operated in connection with the centre-line indicator controller which clearly shows deviations from a controlled valve even at a moderate distance. When the plant is "on-control", the pointer lines up with a fixed datum on the centre-line of the scale so that an operator can check a number of instruments with a single glance. One version is designed for applications where "on-off" control is inadequate but where the expense of continuous regulation of power input is not justified. It can be applied to the control of many factors such as gas composition, *p*H and pressure, and is particularly suited to temperature control. Effective scale length is 20 in. (510 mm), but in the special model for gas analysis it is 15 in. (380 mm). Maximum ambient operating temperature is 35°C (95°F). The indicator, basically, is a well-proven industrial millivoltmeter movement. By optically projecting a small portion of the scale on to a translucent screen, the instrument, which is less than 8 in. wide, is given a scale length of 20 in. The scale is adjustable to bring the desired value in line with a central datum. To eliminate parallax, the pointer is projected on to the same screen. Light from the projector lamp falls on a photocell and is partly interrupted by a metal shutter carried by the pointer. The cell resistance thus varies in accordance with the pointer position. **Cambridge Instrument Co. Ltd., 13 Grosvenor Place, London, S.W.1.**

BCE 5340 for further information

Disperser Development

The Szegvari Attritor, for which Torrance & Sons recently obtained the sole manufacturing rights for the United Kingdom, British Commonwealth and other countries, is now fitted with a variable-speed gear attachment. **Torrance & Sons Ltd., Bitton, near Bristol.**

BCE 5342 for further information

Tantalum and Zirconium Heat-transfer Tubes

Murex can supply welded tantalum and zirconium tubes in a wide range of diameters and in various wall thicknesses. Welded tubes are generally satisfactory in most heat-transfer units and it is only where exceptionally high pressures are used that solid drawn tubes are preferred, the company point out. Minimum diameter for fusion and resistance welded tantalum tubes is ½ in., and for zirconium is ¾ in. Minimum wall thickness for both metals in fusion welded tubes is 0.025 in. and in resistance welded tubes 0.005 in. **Murex Ltd., Rainham, Essex.**

BCE 5343 for further information

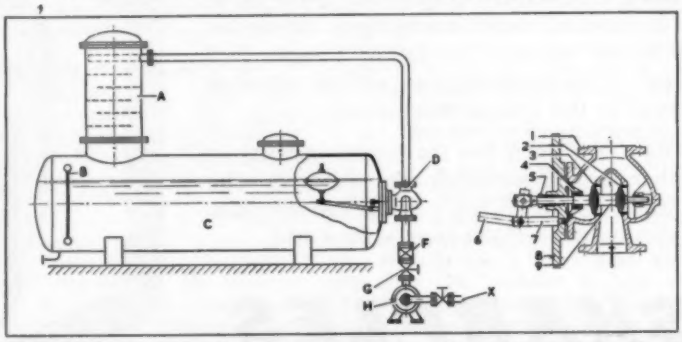
Belt-driven Mills

KEK have introduced a belt-driven series of pulverisers similar to their gear-driven predecessors in the design of the grinding parts. The reinforced rubber

Float Valves

Equipment for working in conjunction with floats fitted inside closed vessels is now available in a number of forms from the German concern of Schneider & Helmecke. Examples include float mechanisms for operating three-terminal switches which form part of the apparatus for controlling liquid level in closed tanks under pressure, low-level alarm, or as a level indicator when used with a direct-coupled scale. In other applications the floats can operate a single-seated or double-seated valve, and in many cases the valve itself can be fitted outside the closed container in which the float operates. The valve is therefore readily accessible. The accompanying diagram shows a typical application of a double-seated balanced valve operated by a float-lever mechanism. The arrangement allows condensate to be fed to a combined deaerator and storage vessel, in which the condensate level is kept constant. The exterior mounting of the valve makes it possible to feed the condensate direct to the deaerator column. Valves of this kind are available in sizes from 1 in. to 8 in. and, if required, the seats, valve spindles and cones, floats and levers and so on can be supplied in corrosion-resisting materials such as austenitic steels. Special linings and coatings can also be provided if required. These fittings are suitable for applications where the liquids have to pass through other apparatus before entering the vessel whose level is controlled. **Schneider & Helmecke, Offenbach-M, Germany.**

BCE 5341 for further information



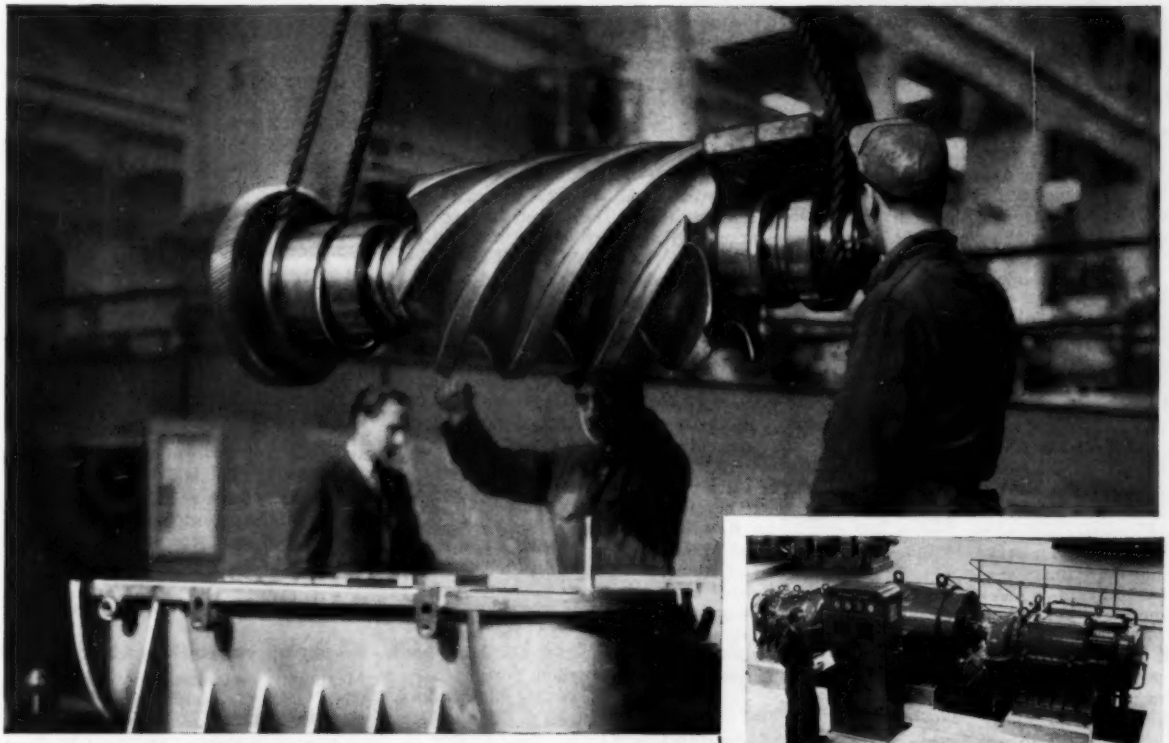
LEGEND: A = deaerator; B = water level gauge; C = feed water storage; D = float valve; G = shut-off valve; X = from condensate sump; 1 = flange; 2, 3 = valve seating; 4 = stem bush; 5 = stuffing box nut; 6 = float arm; 7 = pivot support; 8 = flange; and 9 = double-seating valve case.

BCE 5276 for further information

A New Rotary Screw Compressor

THE ATLAS COPCO

TWIN-AIR



Fitting the female rotor in a Twin-Air compressor.

NO METALLIC CONTACT BETWEEN COMPRESSION COMPONENTS— this means *no wear*... long intervals between overhauls... minimum maintenance.

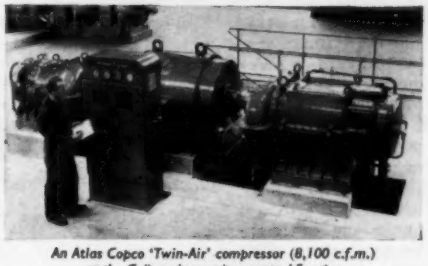
HIGH EFFICIENCY — cuts power waste—and operating costs.

SPACE SAVING — simple, compact design effects marked reduction in installation costs.

SMOOTH AIR FLOW — no 'surging' or 'pumping' characteristics.

OIL-FREE AIR OR GAS — no lubricant is present in the compression chamber.

LESS SENSITIVE TO IMPURE AIR — because compression components are not in metallic contact.



An Atlas Copco 'Twin-Air' compressor (8,100 c.f.m.) at the Grängesberg mine, central Sweden.

BASED ON A SWEDISH INVENTION

Atlas Copco Twin-Air compressors—based on the original design of the Swedish Inventor, Lysholm—have already been fully tested at Kiruna in the Arctic Circle area of Northern Sweden. Here, at the world's largest underground iron mine, they have been operating under normal working conditions for two years.

NOW A TWIN-AIR PORTABLE!

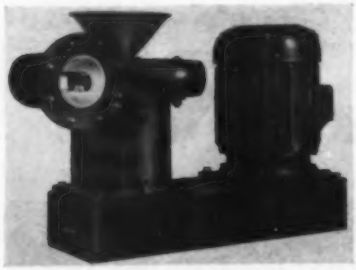
Atlas Copco introduces the *world's first* PORTABLE Rotary Screw Compressors! These portable machines embody all the know-how gained from two years operating experience with Twin-Air Stationary Compressors. The first models in this new range are machines of 370 c.f.m. and 620 c.f.m. Both 100% air-cooled, diesel-powered units.

Atlas Copco PUTS COMPRESSED AIR TO WORK FOR THE WORLD

For details of the new Atlas Copco Rotary Screw Compressors, contact your local company or agent or write to Atlas Copco AB, Stockholm 1, Sweden, or Atlas Copco (Great Britain) Limited, Beresford Avenue, Wembley, Middlesex

C.55/8

PLANT EQUIPMENT NEWS



belt is fitted with teeth which fit into slots on the motor and pulveriser pulleys, and the makers state that the new drive provides at least a 20% increase in output horsepower. Frequently, under normal working conditions, they report, a 50% increase has been obtained and the performance has well exceeded the designer's expectations. The 4B and 3B machines cover a range of throughput in continuous productions of 200-2000 lb. hour. **KEK Ltd., Palmerston Street, Manchester, 12.**

BCE 5344 for further information

New Oil Burners

By agreement with the General Metals Corp. of the U.S.A., Swinney-Enterprise rotary oil burners are to be manufactured in Britain. These burners are of the horizontal, belt-driven, rotary-cup type. The range comprises 12 different sizes, and the burners are capable of handling the heaviest grades of liquid fuel over the range of 3.5 to 167 gph. Realistic turn-down ratios of approximately 4 to 1 are claimed for the burners with good performance, high CO_2 and low smoke numbers throughout the operating range.

Fully modulating or high-low operation can be provided for all sizes. Automatic on-off operation is limited to burners up to maximum output of 25 gph. An integral variable-output fuel metering pump ensures that the correct quantity of fuel is supplied to the burner throughout its output range independent of changes in oil supply pressure or temperature. It is believed that this is the first rotary burner with such a device to be marketed in this country.

BCE 5345 for further information

PTFE Dispersions

To avoid the need for a sintering temperature of 400°C in making adherent PTFE films, Acheson Colloids are now producing Emralon dispersions of PTFE. This allows the PTFE films to be applied to heat-sensitive surfaces. It is also stated to give improved adhesion, greater resistance to wear and to corrosion. It thus opens up a range of industrial applications where the potentialities of PTFE coatings were recognised but could not formerly be exploited as a dry film lubricant for scientific instruments, conveyors, chutes, roll surfaces and others.

Emralon 810, employing a phenolic binder, is applied by air spray and requires curing for one hour at 150°C. The green coatings produced are tough and flexible. Emralon 820, which can be applied by spraying or dipping, contains a thermoplastic binder and needs no heat curing. The turquoise coating hardens in air at room temperature in two hours.

Trial packs and information on these dispersions can be obtained from **Acheson Colloids Ltd., P.O. Box No. 12, Prince Rock, Plymouth.**

BCE 5346 for further information

Extruder for Testing Smoothness of Dispersions

The FIRA/NIRD extruder is used to force test material through an orifice at a constant speed. The thrust required is continuously measured and recorded on a paper chart, which then provides a permanent record of the behaviour of the material throughout the test.

The smoothness of this trace line is an indication of the smoothness of the material under test. The area under the curve is a direct measure of the work done during extrusion.

By means of a series of five interchangeable calibrated leaf springs, materials with a very wide range of textures can be examined. This instrument was developed by the National Institute for Research in Dairying and the British Food Manufacturing Industries Research Association for testing foodstuffs, but it should be capable of application for measuring the texture of any material capable of being forced through an orifice. **H. A. Gaydon & Co. Ltd., 93 Lansdowne Road, Croydon, Surrey.**

BCE 5347 for further information

Adjustable Small Vibratory Feeder

Laboratory applications are considered to be particularly suitable for a new magnetic vibratory feeder with an output adjustable between zero and 1500 lb. per hour for sand or a free-flowing material having a bulk density of about 100 lb.

per cu. ft. The unit is claimed to give accurate control of the feed and instantaneous cut-off, so that it is usable in automatic weighing operations.

There are no moving parts except springs, and the feed trough can be totally enclosed and dustproofed when necessary. The trough, of stainless or mild steel, chromium-plated brass or plastic-coated steel, can be of any reasonable width and up to 12 in. long. The feeder consists of a heavy cast base to which are attached two leaf springs supporting the feed trough, and the assembly operates at its natural frequency of 3000 cycles per minute.

Price ranges from £30 upwards, depending upon the type of trough to be fitted. **Sinex Engineering Co. Ltd., 12 Rochester Row, London, S.W.1.**

BCE 5348 for further information

Diversion Valves

Maximum permissible pressure and temperature of the heating medium used with the Spirax-Sarco type 57 diversion valves are 250 psi and 360°F. In operation, the valve is controlled by a Sarco thermostat employing direct hydraulic expansion to operate four poppet valves through a push rod, rack and rocking levers. Water enters the "inlet" port and leaves the two "outlet" ports in proportions determined by the position of the poppet valves. Two of those poppet valves work in opposition for each "outlet" port, ensuring complete balance at all times and eliminating flashing and water-hammer caused by the sudden closing of unbalanced valves. The thermostat can be calibrated anywhere between 0°F and 300°F, and an adjustment range of ±50°F from the calibrated temperature is available. The valve controls the temperature of calorifiers, heater batteries and process plant working on high- and medium-temperature hot water. **Spirax-Sarco Ltd., Cheltenham, Gloucester.**

BCE 5349 for further information

High-pressure Flowmeters

Maximum working pressure of 6000 psi over the temperature range of −40°C to +120°C is reported for the high-pressure flowmeters produced by the Gloster Aircraft Co. Ltd. The flowmeters are suitable for the majority of fluids and oils; liquid foods, chemicals, water, kerosene and toothpaste are quoted as examples. The metering unit consists of a main body in which is housed a tapered sliding plug held in the closed position in a sharp-edged orifice by a main control spring. Fluid passing through the meter overcomes the spring force, thus displacing the plug as a function of flow. The movement of the plug is transmitted to the indicator unit by means of a potentiometer (the slider being lightly spring loaded against the plug spindle) through a direct-current balanced bridge network. The electrical supply is self-contained, power being obtained from two 1.5-volt dry cells. Type numbers TDD 101/1 and 101/21 deal with 0.5 to 5 gpm; 101/2 and 101/22 cover 1 to 10 gpm. Other models range up to 30 gpm. Accuracy is given as ±2% from 25% of full scale, and ±5% for the first ¼ of full scale. **Gloster Aircraft Co. Ltd., (Technical Developments Division), Gloucester.**

BCE 5350 for further information

pH and Quality Control

In many processes and undertakings pH plays an important part in determining quality and yield. Among the benefits to be gained from automatic control of pH are : improved quality and uniformity, reduction of waste, conservation of reagents; and protection from corrosion or pollution.

The Kent Universal pH Indicator/Recorder/Controller is a typical example of the many contributions made by KENT towards fully automatic adjustment of a plant's physical conditions. It is an accurate, robust and dependable equipment incorporating an air-operated controlling unit which automatically corrects any deviation in desired pH value by means of a regulating unit. The regulating unit can take the form of a diaphragm-operated control valve for direct installation in the pipe-line, a power cylinder for operating valves etc., or an open dosing trough for regulating reagent feed.

NEW miniature primary element for flow-line and immersion

KENT have recently introduced this miniature primary element for pH measurement, using a glass electrode as the pH responsive element. The use of electrodes which are extremely robust and long lasting is possible because of the sensitivity of the KENT continuous-record measuring system.

Both electrodes and resistance thermometer are permanently sealed into an easily replaced and inexpensive assembly unit. The element is completely impervious to water vapour; can be totally immersed in boiling solutions for long periods with very little maintenance.

Further information is given in Publication BC 158, obtainable on request.

KENT

for the control of variables

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Factories, Subsidiary Companies, and Branch Offices in

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PLANT EQUIPMENT NEWS

Porous Carbon Filter Tubes

A complete line of porous carbon filter tubes is now available directly from Union Carbide International Co., Division of Union Carbide Corp. A wide variety of styles suited to any type of tube filtering equipment can be supplied with any desired internal or external machining. Porous carbon filter tubes 36 in. (91.4 cm) long of any internal diameter and up to 6⅝ in. (16.8 cm) outer diameter can be machined from available stock. In addition, grade-40 porous carbon counterbored filter tubes, with 2⅛ in. (5.4 cm) inner diameter and 4½ in. (11.4 cm) outer diameter, 36 in. long (91.4 cm), are carried in stock for immediate delivery. Typical configurations of porous carbon filter tubes include plain open-end tube, blind-end tube, counterbored tube, and blind-end tube with a collar flange. **Union Carbide International Co., New York, 17, N.Y., U.S.A.**

BCE 5351 for further information

Metal Power Couplings

The new series, CN, all-metal Metastream flexible power transmission coupling is available in bore sizes at present up to a maximum of 1¼ in. The maximum hp/rpm rating is 0.010. Transmission membranes can be removed from the coupling without disturbing the driving or driven units. The makers state that the couplings are very resistant to corrosion, require no lubrication and employ no rubber bushes, springs, gears or chains. **Metaducts Ltd., Catherine Wheel Road, Brentford, Middx.**

BCE 5352 for further information

New Moulding Material

Bakelite are making available a new fast-curing glass-fibre mineral-filled polyester dough-moulding material, DX 18927. They state that the new material combines high mechanical strength and excellent electrical properties with good water resistance, track resistance and dimensional stability. Although not quite as strong mechanically as more conventional alkyd or phenolic glass-fibre reinforced moulding materials, DX 18927 mouldings are cheaper to produce and the material, in many ways, is easier to handle and mould, since it is soft and can be readily preformed by hand without pre-heating. **Bakelite Ltd., 12 Grosvenor Gardens, London, S.W.1.**

BCE 5353 for further information

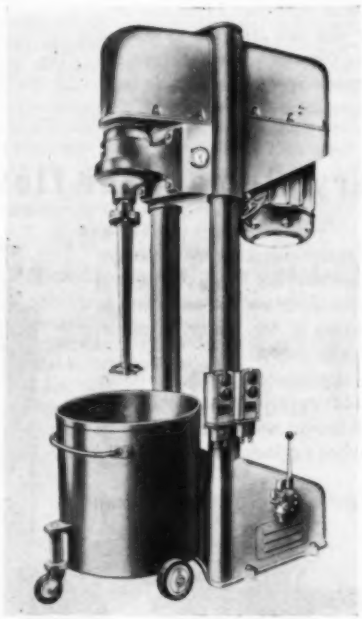
Automatic Amino-acid Analyser

Two major components, the chromatographic equipment and the analyser unit, comprise the new, improved commercial apparatus for the ion exchange chromatography of amino acids and related compounds, based on the Spackman-Stein-Moore system for separation of mixtures of amino acids including protein hydrolysates, tissue extracts or biological fluids. The chromatographic equipment is basically represented by the ion-exchange columns packed with classified resin and adjustable precision pumps for buffer and reagent supply. The analyser unit consists basically of the flow-photometer assembly and the multipoint recorder. The flow-photometer is designed to detect the absorbance of the continuous effluent stream at the different wavelengths of 440 mμ and 570 mμ. A precision flow-type absorption cell enables the effective light absorption path of a third detector to be shortened, thus providing a wide range of sensitivity. The complete flow-photometer assembly is thermostated to ensure highest accuracy. The multi-point recorder prints three separate absorbance curves in different colours, each colour representing the absorbance at a specific wavelength. A special printing feature allows easy integration of the curve areas for fast qualitative and quantitative evaluation. **Phoenix Precision Instrument Co., 3803-05 North 5th Street, Philadelphia, 40, Pennsylvania.**

BCE 5354 for further information

High-speed Disperser

A disperser which provides a peripheral impeller speed of 3500-7000 fpm has been introduced by Steele & Cowlishaw. The range is suitable, the manufacturers state, for all types of dispersions where a solid is to be mixed with a maximum of solvent. In addition to the 1-gal. bench model, the design is available in a 5-gal. model using a 20-hp motor and a 100-150-gal. model equipped with a 45-hp motor. **Steele & Cowlishaw Ltd., Cooper Street, Hanley, Stoke-on-Trent.**



BCE 5355 for further information

New Publications

Vinyl's Technical Service Report T-3 deals with the bulk storage and handling equipment for vinamul polyvinyl acetate emulsions. Details of tanks, pumps, pipelines and their fittings, care of the equipment and a list of manufacturers and contractors of the equipment are included. **Vinyl Products Ltd., Butter Hill, Carshalton, Surrey.**

BCE 5356 for further information

A useful publication from British Resin Products is their recently-released Technical Note P202. This gives details of the chemical resistance of Cellobond polyester resins, laminates and casts which are known to offer excellent resistance to chemical fumes and liquids. Copies from the **Information Dept., British Resin Products Ltd., Piccadilly, London, W.1.**

BCE 5357 for further information

Brooks Rotameter have sent us a copy of their new bulletin (170) which contains a résumé of the major advantages of the Rotameter as a flow-measuring device and descriptions of their MPT series of transmitter extensions which, according to Brooks, because of an entirely new principle for flow signal transmission, opens up many new applications for the Rotameter. Copies are available from **Brooks Rotameter Co., Box 432, Lansdale, Pennsylvania.**

BCE 5358 for further information

For those interested in the Free Trade Area, a report prepared by the Economist Intelligence Unit Ltd for the Federal Trust for Education and Research will prove to be an intriguing document, as it purports to describe the similarities and differences between the U.K.'s existing tariff and the E.E.C. tariff as it will be at the end of the transition period, around 1970-2. External tariffs are reported to be one of the biggest stumbling blocks in the way of co-operation between the U.K. and the Common Market six in a Free Trade Area. This report, it is said, provides the necessary data to form a considered opinion of the importance of these existing differences and the possibilities of reconciling them. Copies, priced 10s. each, may be obtained from the **Federal Trust for Education and Research, 10 Wyndham Place, London, W.1.**

BCE 5359 for further information

The problem of collecting and disposing of ash and fine dust from P.F. boilers of the dry-bottom type is solved in boilers with continuous slagging furnaces, in which the whole of the ash and dust produced by the combustion of the pulverised fuel are converted into slag. This is discharged continuously from the furnace, quenched and disintegrated in the process to an easy-to-handle pellet-like mass of industrial value. Details of furnaces of this type are given in a recent Simon Carves publication, "Water-tube Boilers with Continuous Slagging Furnaces". **Simon Carves Ltd., Cheadle Heath, Stockport, Cheshire.**

BCE 5360 for further information

Men with a lot of liquids to handle know that with ENSECOTE size is no obstacle. Full ENSECOTE protection can now be applied economically to almost any size of tank. For stoving, we have one of the largest furnaces in the country—it's all part and parcel of our major development programme. We can also of course make and erect the tanks—*any* kind of tanks, including fibre glass, P.V.C. and polythene—often saving you time and money.

ENSECOTE linings protect almost anything you can put into a tank. They are easily cleaned and sterilized, completely odourless and tasteless, and will add years to a tank's life.

ENSECOTE *Lithcote* PLASTIC LININGS

For literature and technical advice write to: NEWTON CHAMBERS & CO. LTD., THORNCLIFFE, NR. SHEFFIELD, ENGLAND

Agents in Belgium, France and Holland: FOURS LECOCQ ET ATELIERS DE TRAZEGNIES REUNIS, S.A., TRAZEGNIES, BELGIUM

Month's News in Brief

Setting for Plastics

In 1958 122,000 tons of plastics (about 30% of the U.K. output), worth more than £32 million, were exported. Britain's total output at present is around 400,000 tons, as against a world output of some 4 million metric tons. Today most industrial countries have thriving plastics industries and the forthcoming International Plastics Exhibition to be held at Olympia, London, June 17-27, will most certainly prove an attractive venue to visitors from these and other countries contemplating the use of plastics materials.

The exhibition will cover every aspect of plastics technology, ranging from raw materials, machinery for the production of finished products, to a convention (running concurrently) at which, among other subjects, will be a discussion on the properties and moulding characteristics of polypropylene, a new material recently announced.

The display of this latter material will be one of the highlights at the exhibition and is bound to excite wide interest among British plastics manufacturers, as the commercial production in this country of this material by the Shell Chemical Co. at their Carrington Refinery is expected some time in 1961.

Thirteen countries and more than 270 manufacturers, suppliers of materials, equipment and products will be represented, included amongst whom are the following: BX Plastics Ltd.; Baker Perkins Ltd.; British Ermeto Corp. Ltd.; British Geon Ltd.; British Oxygen Chemicals Ltd.; The Distillers Co. Ltd. (Chemical Division); Endecotts (Filters) Ltd.; Fibreglass Ltd.; Imperial Chemical Industries Ltd. (Plastics Division); Marston Excelsior Ltd.; Shell Chemical Co. Ltd.; and Whiffen & Sons Ltd.

Underground Gas Storage

Work carried out by the I.C.I. Cassel Works Brinefields Section to prepare a giant cavern 1250 ft down in the Port Clarence salt measures for the storage of 10 million cu. ft of gas by the Northern Gas Board is complete and domestic and industrial users may soon be drawing supplies from this underground gasholder.

The cavern, which is the first man-made underground gasholder in Europe, is almost directly below the north shore of the Tees estuary, near the Seal Sands. The General Chemicals Division has for many years pumped brine from the salt measures in the Port Clarence area for use in Cassel Works and more recently at their Bain Works at Wilton and, as a result, large cavities have been formed underground. A cavity of the desired shape and about 350,000 cu. ft in size has been dissolved out of the rock salt at a depth of about 1250 ft and the Northern Gas Board have constructed a high-pressure gas compression plant nearby which is connected by pipeline to their trunk gas mains linking Teesside and other areas in South Durham. The pumping of gas was started early in February and the first few weeks were taken up displacing brine which filled the cavity.

The scheme will be used by the Gas Board to assess the economics and practicability of this method of storage, which possibly could be extended to even out seasonal changes in demand.

Refinery Gas for N.W. Gas Board

Heads of Agreement have been concluded between the North Western Gas Board and the Shell Refining Co. whereby Shell will supply gas from Stanlow Refinery, near Chester, to the North Western Gas Board at their works in Ellesmere Port. The agreement will take effect from mid-1960 and cover a period of ten years. Stanlow Refinery will supply between 12 million and 24 million therms a year to the Gas Board—equivalent to 70 to 140 tons of treated gas per day. In order to meet these new demands, Shell will construct a new gas-treating plant at Stanlow Refinery and will deliver gas to the refinery boundary. The Gas Board will build a new pipeline from there to their works at Ellesmere Port, where the gas will be processed for inclusion in the Board's grid system for ultimate use by consumers.

Heat-exchange Equipment

In the table "A Guide to the Availability of Heat Exchange Equipment", published in our March issue, the names of W. C. Holmes & Co. Ltd., Turnbridge, Huddersfield, and W. C. Heraeus Platinschonelze G.m.b.H. (agents: New Metals & Chemicals Ltd., Chancery House, Chancery Lane, London, W.C.2) became transposed under the heading annular heat exchangers, p. 156. Holmes supply that type of equipment in cast iron, and Heraeus in aluminium, tantalum, titanium and zirconium.

Expansion at Whitehaven

Solway Chemicals Ltd. have decided to expand their sulphuric acid and cement capacity at Whitehaven by 50%. Their existing plant, which was started up in 1955, is producing both sulphuric acid and cement at the rate of 100,000 tons a year.

New Udex Unit in Operation

A Udex unit is now in operation at Stanlow refinery at Ellesmere Port, near Chester, England, for the production of an aviation gasoline blending component. It is the first of its kind in any Shell refinery. Construction of the Udex unit, which cost about £800,000, began at the end of 1957 and it has just completed a trouble-free acceptance trial. The unit incorporates six columns, the tallest a 120-ft solvent stripper, and has a capacity of 1000 tons daily. It was designed by Universal Oil Products Co., of Des Plaines, Illinois, U.S.A.

The Udex unit employs solvent extraction with a special solvent mixture of di-ethylene glycol, di-propylene glycol and water. The feedstock, which is a product of the Stanlow platformer, will be extracted with this glycol mixture which preferentially dissolves the aromatic components of the feedstock. The aromatic extract is distilled off from the solvent and used in aviation gasoline, whilst the insoluble non-aromatic portion, or raffinate, will be used as an additional feedstock for other processes.

Udex unit at Stanlow refinery.

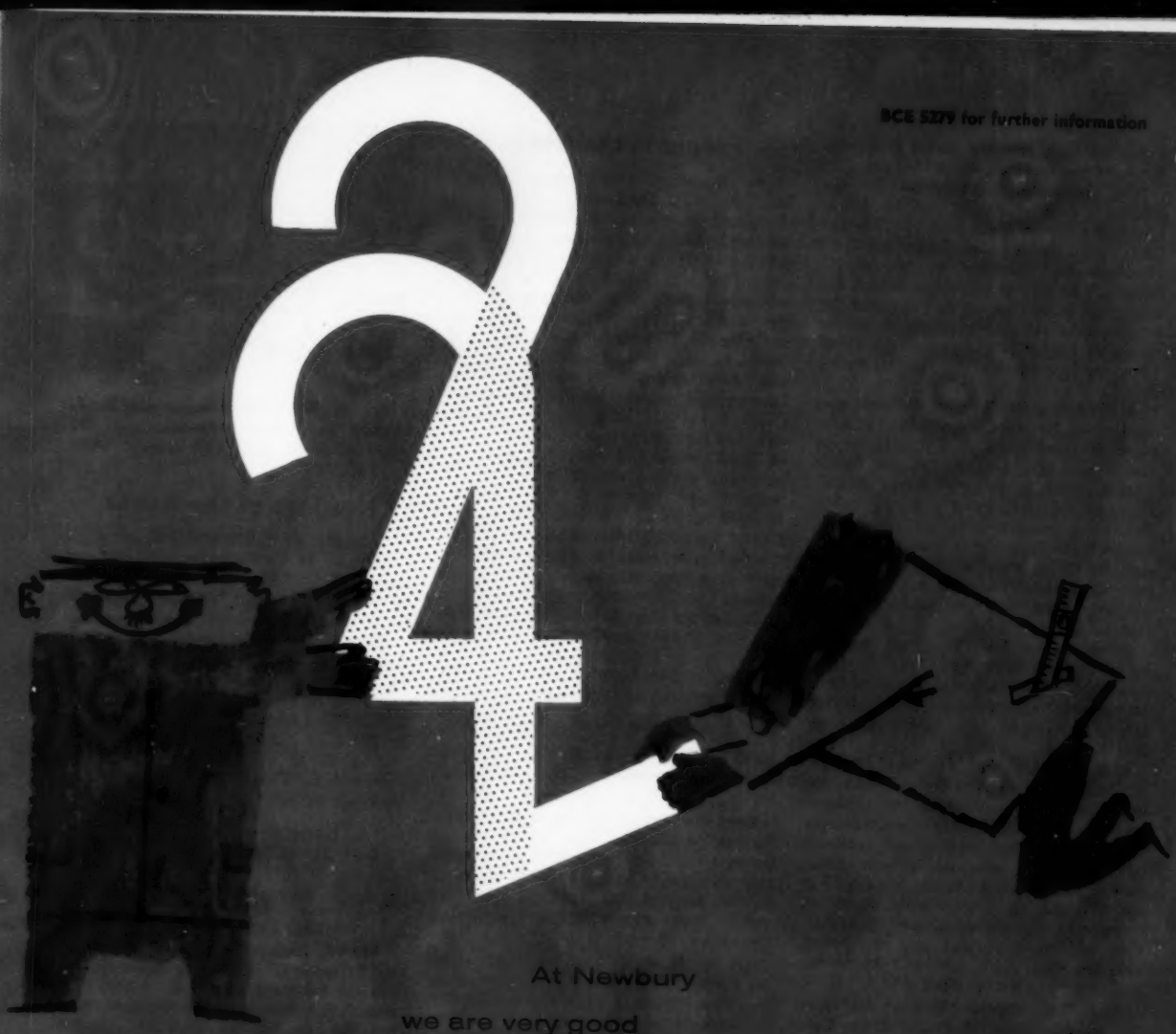
News Briefs

The scope of the U.K. Atomic Energy Authority's Radio-chemical Centre has been widened to form a single comprehensive organisation for producing and marketing all radioactive isotopes. The centre has its headquarters and principal laboratories at Amersham and will have irradiation facilities at Harwell and at other Authority sites. Dr. W. P. Grove is appointed director of the reorganised Radiochemical Centre.

John Brown & Co. Ltd. have received a contract from the U.K. Atomic Energy Authority, Industrial Group, for the refuelling machine for the advanced gas-cooled reactor at Windscale.

Residential courses shortly to be held at the National College of Rubber Technology, Holloway Road, London, N.7, will be devoted to the following subjects: (1) fundamentals of polymerisation processes (July 6-15); (2) basic rubber technology for sales, buying, costing and planning staff (July 6-15); and (3) basic plastics processing (July 15-24). Participants will be accommodated in the College's hall of residence, Carleton Grange, Tufnell Park, London, N.7.

BCE 5279 for further information



At Newbury
we are very good
at putting 2 and 2 together
and making 4 (as you can see).
That is why we welcome any kind of gearing problem.
It might be that the answer
lies in one of our standard range of units,
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Further details are obtainable from the Head of the College.

New laboratory extensions to the research department of I.C.I. Alkali Division at Winnington, Northwich, Ches., were opened recently by Sir Cyril Hinshelwood, President of the Royal Society. The new laboratories, which extend over 20,000 sq. ft, will increase the area of laboratory space available to the Research Department by about a third. They are housed in a three-storey building.

A 100,000 cu. ft Wiggins dry seal gasholder has just been completed by Ashmore, Benson, Pease & Co., member of The Power-Gas Group, for the North Thames Gas Board at Canvey Island. The gasholder will be used in connection with the experiment for importing methane in liquid form from across the Atlantic. It is able to operate at subzero temperatures and it will store the gaseous bleed-off from liquid methane storage tanks.

Power Jacks Ltd. will now operate again from Valetta Road, Acton, London, W.3, and will be self-contained, its manufacturing, engineering, accounts and sales departments all operating from that address.

Hall & Hall Ltd., Oldfield Works, Hampton, Middx., state that they are undertaking a re-equipment and modernisation scheme to satisfy the increasing demand for their rubber and synthetic rubber sealing products. Their Automobile Gasket Division has been sold to the Engineering Components group of companies. The industrial gasket production will be continued and developed, and the trade-mark Hallite remains the property of Hall & Hall Ltd.

The U.K. Atomic Energy Authority has awarded to W. J. Fraser & Co. Ltd., Romford, Essex, a contract for the design of a plant for the recovery of radioactive cæsium from highly active waste materials produced in the processing of irradiated fuel. Over the past few years several Fraser engineers have attended the Authority's training schemes and, now back in the organisation, will play their part in designing this plant. Three further senior engineers from the company have started a one year's course with the Industrial Group on the design of fuel reprocessing plants.

Carter Refrigeration & Airconditioning Ltd. and its subsidiary company, The Midland Heating & Ventilation Co. Ltd., have reformed their operations into a holding company and four operating subsidiaries. The holding company is Carter Thermal Industries Ltd., and the operating companies are Carter Refrigeration Display Ltd., Carter Thermal Engineers Ltd., Carter Refrigeration & Airconditioning Ltd., and The Midland Heating & Ventilation Co. Ltd.

Alfa-Laval Co. Ltd., Great West Road, Brentford, Middlesex, report that their telephone number has been changed to Isleworth 1221.

Charles Page & Co. Ltd., of London, Manchester and Glasgow, have been appointed sole U.K. agents by The Texas-U.S. Chemical Co. for the sale of Synpol synthetic rubber and butadiene.

People in the News

The Board of Trade announce that **Mr. J. C. Duckworth** has been appointed as managing director of the National Research Development Corporation. Mr. Duckworth, who is 42 years old, has had a distinguished scientific career. After taking First-class Honours in Physics at Oxford in 1938, he played a leading part in radar research and development during the war. After the war he was engaged in fundamental nuclear physics research at Chalk River in Canada and at Harwell, and was later in charge at Ferranti Ltd. of development and design of the guidance and control system of the guided weapon now known as "Bloodhound". In 1954 he joined the then British Electricity Authority with responsibility for the design, construction and operation of nuclear power stations, and he is at present Chief Research and Development Officer of the Central Electricity Generating Board. **Mr. D. Hennessey** has been appointed by the Corporation to a new post of deputy managing director. Mr. Hennessey, who was a former Principal Patents Officer at the Ministry of Supply, joined the Corporation's staff in 1950 at the age of 38 and was made an executive member of the Corporation in 1956.

Lord Plowden, chairman of the Atomic Energy Authority since 1954, is to become chairman of British Aluminium and vice-chairman of Tube Investments at the beginning of 1960. His term of office with the A.E.A. expires on December 31 next.

Dr. L. B. Pfeil (director, The Mond Nickel Co. Ltd.) has been awarded the Institute of Metals (Platinum) Medal in recognition of his outstanding contributions to non-ferrous metallurgical science and to the non-ferrous metals industries. The Rosenhain Medal has been awarded to **Professor R. W. K. Honeycombe** (Professor of Physical Metallurgy, University of Sheffield) in recognition of his outstanding contributions in the field of physical metallurgy. The W. H. A. Robertson Medal and Premium has been awarded to **Dr. R. B. Sims** (chief engineer, Davy & United Engineering Co. Ltd.) for a paper on "Automatic Gauge Control in Rolling Mills", published in the *Journal of the Institute of Metals*, 1957-58.

The following members have been elected to fill vacancies on the Council of The Institute of Metals: *President:* **G. L. Bailey** (director, The British Non-Ferrous Metals Research Association). *Past President:* Marshal of the Royal Air Force **The Lord Tedder** (Chancellor, University of Cambridge; chairman, Standard Motor Co. Ltd.). *Vice-Presidents:* **Hugh Ford** (Professor of Applied Mechanics, Imperial College of Science and Technology, University of London); **E. H. Jones** (joint managing director, Capper Pass & Son Ltd., North Ferriby); and **H. O'Neill** (Professor of Metallurgy, University College of Swansea, University of Wales). *Honorary Treasurer:* **D. P. C. Neave** (director, The British-American Co. Ltd., Capper Pass & Son Ltd., James Bridge Copper Works Ltd. and Wolverhampton Metal Co. Ltd.). *Ordinary Members of Council:* **W. O. Alexander** (assistant research manager, Imperial Chemical Industries Ltd., Metals Division, Birmingham); **N. P. Allen** (superintendent, Metallurgy Division, National Physical Laboratory, Teddington); **F. Dickinson** (manager, Development and Research Department, The Mond Nickel Co. Ltd., London); and **L. Rotherham** (research member of the Central Electricity Generating Board, London).

Mr. R. W. Holmes and **Mr. T. J. Lawson** have been appointed to the board of directors of The English Glass Co. Ltd.

Meetings of the Month

Society of Chemical Industry

May 4. At 14 Belgrave Square, London, S.W.1. "The 'Conveyor' Concept of Water in Industry", by E. L. Streatfield. **6.30 p.m.**

May 5. At 14 Belgrave Square, London, S.W.1. "The Pursuit of Polymers", by C. E. Hollis. **6.30 p.m.**

May 6. At 14 Belgrave Square, London, S.W.1. "Corrosion as a Design Problem", by Dr. S. G. Clarke. **6.30 p.m.**

May 12. At 14 Belgrave Square, London, S.W.1. "Fuel Economy in Chemical Works", by W. Quick. **6 p.m.**

Institute of Petroleum

April 21. At 61 New Cavendish Street, London, W.1. "Oil in the Gas Industry", by Dr. J. Burns. **5.30 p.m.**

The Physical Society

May 7. Joint meeting with Institute of Refrigeration. At The Institute of Marine Engineers, 76 Mark Lane, London, E.C.3. "Handling Cryogenic Liquids for Rocket Engines", by D. Hurden. **5.30 p.m.**

Coming Events

April 27-30. At Royal Horticultural Society's New Hall, Greycoat Street, London, S.W.1. Corrosion Exhibition organised by "Corrosion Technology".

May 5-9. At North British Hotel, Princes Street, Edinburgh. Oil and Colour Chemists' Association Biannual Conference.

May 6-7. Open days of the Water Pollution Research Laboratory, Elder Way, Stevenage, Herts.

May 11-13. At the Central Hall, Westminster, London, S.W.1. Institution of Chemical Engineers' Joint Symposium on Instrumentation and Computation in Process Development and Plant Design.

May 11-14. Institute of Fuel Conference at Torquay. "Major Developments in Liquid Fuel Firing 1948-1959."

May 14-23. At Tulsa, Oklahoma, U.S.A. International Petroleum Exposition.

May 21-27. At Earl's Court, London, S.W.5. Institute of Electrical Engineers' International Scientific Convention and Exhibition on Transistors.

May 25-27. At 6 rue Paul Valiry, Paris, 16. Institute Technique du Batiment et des Travaux Public International Conference on Heating, Ventilating and Air Conditioning.